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OF THE EIGHTEENTH
EXPLOSIVES SAFETY SEMINAR

VOLUME I

EL TROPICANO MOTOR HOTEL
SAN ANTONIO, TEXAS

12-14 SEPTEMBER 1978

SPONSORED BY

DEPARTMENT OF DEFENSE EXPLOSIVES SAFETY BOARD

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(6) MINUTES OF THE

EIGHTEENTH EXPLOSIVES SAFETY SEMINAR

Volume I.

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PREFACE

This Seminar is held as a medium by which there may be a free exchange of information regarding explosives safety. With this idea in mind, these proceedings are being provided for your information. The presentations made at this Seminar do not imply indorsement of the ideas, accuracy of facts presented, or any product, by either the Department of Defense Explosives Safety Board or the Department of Defense.

P. G. KELLEY, JR.
Colonel, USA
Chairman

These proceedings are published for information as an accommodation to the participants at the Seminar. The Department of Defense Explosives Safety Board cannot accept responsibility for the correctness of those papers which have been directly reproduced from copy furnished by the authors.

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WELCOME

COL P. G. Kelley, Jr., USA
Chairman
Department of Defense Explosives Safety Board

May I extend my personal welcome and that of the Department of Defense Explosives Safety Board to you ladies and gentlemen. It is our hope that the Eighteenth Explosives Safety Seminar will continue the excellent tradition of previous seminars - a forum for the exchange of technical data and explosives safety experience between members of the Department of Defense, other U.S. Governmental agencies, civilian industry, and our visitors from overseas.

To begin our seminar, we are honored to have Mr. Fliakas as our keynote speaker.

KEYNOTE ADDRESS

By

Perry J. Fliakas

Deputy Assistant Secretary of Defense

(Installations & Housing)

At

Eighteenth

Explosives Safety Seminar

San Antonio, Texas

September 12, 1978

Colonel Kelley, Ladies and Gentlemen - Good Morning

It is a distinct pleasure for me to address this Explosives Safety Seminar today. I would like to express Secretary White's sincere regrets to all of you that he had to go out of the country and cannot be here. I know that he would have enjoyed meeting you, and taking part in the many activities of this seminar, both technical and social which Colonel Kelley and the members and staff of the Board have arranged in their typically excellent fashion.

San Antonio is a particularly interesting and lovely city and I hope you all have a chance to visit its many historic and beautiful sites while you are here. I hope that I can meet many of you during the day today and this evening.

This is the 19th year of the Explosives Safety Seminar which started as a small scale conference at the Naval Ordnance Station, Indian Head, Maryland in 1959. Its importance and its attendance have grown dramatically since that time. This growth has been appropriate.

Explosives in all forms are one of the most dangerous physical materials with which mankind must

live - whether they be in the form of fuels, entertainments such as fireworks displays or military weapons. They require respect and they require our most stringent study and efforts to assure maximum safety in their handling. I am sure you will all put forth such study and effort during this seminar.

From the viewpoint of the Department of Defense, it is particularly gratifying to note the attendance here of so many representatives of other nations and of industry. We have a mutual interest in advancements in technology and improvements in equipment which will produce less hazardous munitions and safer working and storage environments.

We are also moving toward increased international standardization of munitions and weaponry. It behooves us, then, to share information in the important area of explosives safety. Independent and duplicative pursuit of research or engineering is not the way to make wise use of limited resources.

Beyond that, as allies, who are engaged in defense efforts with a common goal, we should be able to interchange and interoperate weapons and equipment; to store ammunition and weapons in one another's magazines or warehouses; and to pursue the other activities common to our operating forces. We should be able to do this

with the complete assurance that all of us have the benefits of the safety efforts and knowledge of everyone else.

At the last seminar, in Denver, 1976, it was my privilege then also to be your keynote speaker. I discussed certain projects that either had been undertaken or appeared to be in the offing to improve explosives safety, and the difficult management decisions involved in allocating funds among these projects and others to increase the morale and readiness of the forces. The problem of competing for scarce funds with other management goals is even more difficult today. I am happy that we and the DDESB can report progress, in some instances substantial progress, on many of these projects.

Improvements are being made in the safety of ammunition storage in a number of areas in which the U.S. Department of Defense has a major interest. These improvements include better protection of the military personnel involved, and a reduction in the hazards to the private sector.

In 1973, a DoD task team including the DDESB made a survey of the U.S. ammunition storage conditions in Europe and found them to be sadly lacking in basic safety requirements. They saw instances of improper

storage which exposed ammunition to accelerated deterioration, to potentially catastrophic fires, and to explosions which might result from the communication of an explosion from unprotected adjacent stocks. As a result of the survey, the DDESB made many strong recommendations for corrective action, recommendations that have been and are being acted upon.

The Military Departments are now in a phase of increasing inventories of ammunition and explosives. Included in this program is a build-up of reserve stocks in many parts of the world and overall increases in most stockpile items. In order that this build-up not recreate the undesirable conditions noted by the survey team in 1973, the Services have undertaken a major igloo magazine construction program, most particularly in Europe.

The initial increments of this program are well underway. We will provide a maximum amount of storage in earth-covered magazines. Experience in Southeast Asia with several major disasters in ammunition storage depots demonstrated anew that the use of the earth-covered igloo is the only practical way of insuring against excessive losses and reducing the size of an explosives incident or accident.

For some years the Services have also been engaged in an extensive program of modernizing and expanding ammunition production facilities.

Modernizing old plants is a particularly difficult problem. Considerations of safety, the environment, and worker health as well as efficiency and production rates compete with the economic considerations of retaining as much of the old plants as possible, working within existing real estate boundaries and generally conserving dollars. I can report that safety is not being overlooked.

Techniques developed by the DDESB and the U.S. Army to increase safety are being used. These techniques often require a considerable increase in capital investment which would not be required for less hazardous facilities, but we are determined that safety will not be slighted. Safety is an investment - not only are people protected but so is the plant. The cost of safety can frequently be justified as the cost of insurance on the physical plant even if people are not considered. And, of course, we do consider people.

With the building of a totally new facility, these constraints can be handled more easily. Sometimes even, costs can be reduced through proper attention to safety. Building structures strong enough to contain accidental

explosions allows a reduction of distance between them. This results in substantial savings in utility lines and real estate. It may even improve production rates by reducing the distances materials must travel.

As a manager this is exactly what I want to see. Designs that improve safety, protect the physical plant, increase productivity and save money. When such a fortutious combination occurs you may be sure that there is no difficulty in selling safety. It is unfortunate that it is not always so clear, or that it does not occur more often.

Over the years you have seen reports of the safety testing programs sponsored by my office through the DDESB or the Military Departments. These test programs have been very fruitful.

They have provided firm safety guidelines and have given us information t : permitted us to reduce the costs of construction. An excellent example of this was the Eskimo test series.

The information from Eskimo tests permitted us to significantly reduce our real estate requirements by placing igloos closer together. By this means we have been able to reduce the estimated cost of magazine construction in Europe by between 15 and 20 million dollars.

As well as reducing land requirements, Eskimo provided information that permits redesign of igloos to less costly structures. About $1 million was saved on two projects which are part of the ammunition plant program as a direct result of the Eskimo tests.

Again this is an excellent example to prove that safety is not always expensive and I congratulate the Board and the Army, Navy and Air Force for their support of these tests and the excellent results that were obtained.

However, every advancement brings us closer to the absolute limit that we can achieve. It does not appear that construction costs or land requirements can be reduced much further. New reductions in spacing will probably only be possible by increasing the strength of the igloos and other types of magazines and this will certainly increase their costs.

In situations where real estate is very expensive or unobtainable these construction cost increases may well be justified, either as cost effective or because of no other feasible alternative. I hope that new technology will permit even further reductions in cost but I am advised that I should not be optimistic.

The advances I have just listed all came about because of efforts to improve the situation within our

current concepts of what is safe. In Denver, two years ago, I also discussed the difficulty of determining an acceptable degree of safety. Risk analysis and quantification still require more study and emphasis.

We have had for many years a concept of safety which required that it be nearly absolute. The U.S. Congress said "safe" would be defined as the average chance of the average individual escaping injury. This has been held to mean that a specific separation in distance is required for a reasonable degree of protection in the event that a certain amount of explosive were to detonate. *Consideration of the probability of the occurence of the incident itself has not been involved.*

That this is a reasonably sound and conservative safety practice cannot be denied. The historical record of the U. S. Military establishment in the fifty years since the Board's creation confirms it. But under this philosophy we had only one standard of safety for the situation where flying fragments were the principal danger rather than blast. We did not distinguish between large and small explosions; between one or many explosions or among the facilities and population at risk. Was it a concentrated, high value facility or a sparsely developed area of low value?

Our standard did not differentiate. It still does not.

It has long been recognized that our quantity-distance standards do not provide uniform protection against the hazards of fragments and debris. Either a fixed distance, depending on ammunition type but independent of quantity is required, or the fragment hazard is ignored. A fixed distance for protection may be wastefully conservative when applied to small stocks, while to disregard the risk entirely is dangerous.

To characterize the dispersal of fragments and debris from accidental explosions is an enormously complicated task. Its size and complexity are the main reasons for the unsatisfactory state of these standards.

Even when the actual fragment hazard can be successfully described, this information will only be useful if it can be translated into a few workable rules, based on reality but balanced against what is attainable, feasible to enforce, not compromising safety but reflecting the true risk. A large order. However, the Board is beginning to make headway.

I am impressed by the work the Board is doing in this area and I encourage more. We will be watching for their results and I will certainly press for the

revision of the safety standards as soon as these results justify such revision.

The first efforts may seem only to provide information that is intuitively obvious. The explosion of a stack of projectiles produces significantly different fragments than a single weapon. But many test programs begin by confirming our intuition - or refuting it. Initial tests with small clusters of ammunition have been completed.

In addition, the Military Departments have investigated specific hazards posed by new weapon systems or unusual storage configurations. In the past three years, for example, the U. S. Air Force tested trailer storage arrangements of missiles with controlled fragmentation warheads. The U. S. Navy studied the fragment hazard from pierside handling operations involving torpedoes. Both of these test and study activities not only met their immediate objective, which was to permit reduction of the quantity-distance criteria for the particular item, but are very useful as pilot studies for the overall evaluation of fragment hazards under "real world" conditions.

I am advised that systematic trends in the data have been discerned and that relationships are being quantified that will enable us eventually to formulate

more meaningful standards. Even this large task can be accomplished with a well thought out carefully planned program of test and evaluation. Again I would like to congratulate the Board. You will receive a paper later in this seminar detailing this work and the results so far obtained.

Describing fragment and debris dispersal is just one of many problems in attempting to refine the approach to explosive safety by greater use of risk analysis and quantification.

Other problem areas are:

- There is inadequate statistical data on the frequency of incidents in particular storage configurations or with particular operations,
- There is insufficient information on the mechanisms of communication of incidents from stack to stack, ship to ship, and magazine to magazine,
- There is often a lack of comprehensive, descriptive information on the population, value, and vulnerability of a site exposed to the potential explosion effects.

It is easy to see that if the amount of explosive is large but an incident has a low probability of occurrence and the exposed site has a relatively low value, conventional quantity-distance protection may

be disportionately costly. On the other hand, the damage to a concentrated target of high value by a much smaller amount of explosive could be very great - unacceptably so if the circumstances are such as to maximize it.

It is thus possible with existing quantity-distance standards to have a situation that is marginally in violation of the standards and would expose a small number of persons or a small amount of property to some small risk. In contrast, another situation may occur in which an exposure is marginally in compliance with regulations but a much larger number of people or a much more vital and expensive installation may be exposed to a large risk. The final results of an explosive incident thus might be more unacceptable in the case of the "in compliance" exposure than for the one not in compliance.

This demonstrates other difficulties with our present overall standards. It is a natural tendency to assume that if we have met the standard we have done our job. We must beware of the complacency that results from this attitude and we must always be alert to the particular site conditions which require greater than normal precautions in some cases and may allow tradeoffs between unnecessary expenses and higher

acceptable risks in others.

The Board does make these logical judgments in their day-to-day activities and I hope they continue to do so and that you do too.

You are scheduled to hear more later in the program about efforts to improve the analysis of risks and prediction of damage. Initial steps are being taken by several nations to change the direction of safety rules and guidelines from the present practice of either overpowering the explosion or running away from it. Prevention and scientific prediction of the statistical risks in order that planners and decision makers can be better informed seems to be the new direction.

These first, somewhat hesitant steps toward using more sophisticated techniques - in some cases techniques yet to be developed - should continue improvements in safety and, at the same time, avoid the excessive costs of arbitrary rules which do not fit practical situations. A potential for damage and injury exists in many situations that cannot be completely eliminated. We must be able realistically to evaluate the maximum credible explosive event. Having done so, we can predict its likely effect on actual surroundings and be assured that our safety dollars are well spent.

A fundamental change in safety philosophy such as I have described will require making some controversial decisions. In some cases, it would probably be undesirable and self defeating, to try to be too exact as to the actual risks being taken.

For example, how do we decide questions such as:

. What is the maximum number of people who can be exposed to a single given risk?

. What dollar cost can we sustain for safety when the risk of loss of life is low?

. What level of individual risk should people be required or allowed to take on the job even though the same people will take greater risks on their own in personal activities?

Our record is good. Compare, since World War II, the experience in DoD and the commercial explosives industry with that of unrelated and generally more prosaic pursuits.

In recent months incidents have occurred throughout the world, which forcefully demonstrate this point. A few examples:

. A collision of two 747 aircraft on the ground resulted in hundreds of deaths.

. A number of explosions in grain elevators killed more than 50 workers.

. The collapse of scaffolding on a construction project killed nearly 50 workers - and finally, in the very recent past,

. A highway tank truck accident resulted directly or indirectly in the deaths of more than 200 persons who were completely innocent of any connection with the cause of the casualty.

These accidents serve to remind us that almost any activity can be extremely dangerous and they point up the necessity of constant vigilance in our more hazardous undertakings.

Our record is good because we work at it.

But it is not our record which concerns us - even though we can be proud of it.

We are concerned with our continuing responsibilities in the years ahead - responsibilities as managers to protect our resources - responsibilities as concerned safety experts to protect our people, to protect other people and to protect their property.

Let us continue to work at it, work hard at it so that we will always be able to look back on a record we can be proud of. I am sure you will.

I wish you luck and success in this seminar and in your future endeavors.

Thank you.

THE US DEPARTMENT OF DEFENSE

SINGLE MANAGER FOR CONVENTIONAL AMMUNITION

"NEW DIRECTIONS IN US DOD LOGISTICS"

An Address By

Major General William E. Eicher

Commanding General, USA Armament Materiel Readiness Command

The US DoD Single Manager for Conventional Ammunition

to the

Eighteenth US DoD Explosives Safety Seminar

12 September 1978

San Antonio, Texas

Good morning. I appreciate this opportunity to talk to you about the new look in Department of Defense conventional ammunition logistics --- what the Single Manager is --- who he is --- what the organization does in terms of the SM mission --- its scope --- and some pertinent statistics. It is not an easy story to tell because it is a complex operation.

I not only want to greet the US representatives, but the representatives of NATO, Australia, Brazil, Canada, Finland, Sweden, Switzerland, and other countries represented at this meeting.

I will begin by making some observations about the ammunition business in general.

Chart 1 - General Observations

INTERNATIONAL INTEREST IN SM - USE OF US TERMS AND ABBREVIATIONS

I trust that what we are doing to improve the management of the US conventional ammunition logistics effort will be of interest to all of you. I offer by way of apology before I begin, any use of abbreviations which we Americans are so fond of using but which are, unfortunately, confusing to people outside our immediate community. I will try to avoid this confusion in my remarks.

SM CONTRIBUTION TO THE SEMINAR

The centralization of a very substantial part of the conventional ammunition operation under a DoD Single Manager has included centralizing the management of the corresponding explosive safety activities. We therefore, have a very real interest in the seminar.

In reviewing the outstanding program which has been put together for this seminar, I could not help but note that the representatives of my Command will be discussing the major explosion at one of my ammunition plants. I trust that at the next seminar we might be able to make a more positive contribution. I would not want you to leave here with the wrong impression. The fact of the matter is that we have a good safety performance record which is better than industry. One of the reasons we picked the Radford Army Ammunition Plant incident is there are aspects of this which relate to new more modern processes which we believe present a "lessons learned" type exchange that has been so effective traditionally in the safety community.

RECENT TESTS OF ACCIDENT AND INCIDENT CONTROL SYSTEMS

Within the past 30 days, a series of events have occurred which demonstrate to my satisfaction that the mechanisms that we have established for joint Service action in handling accidents and incidents is working. Just last month we had an incident involving Air Force bombs stored at one of the wholesale locations operated by the Army which comes under my DoD Single Manager Charter. The interservice teamwork which has brought elements of the Air Force, Army, and Navy into play has been excellent.

NEW DIRECTIONS

We are completing our first year's operation as Single Manager for Conventional Ammunition. The centralization of the conventional ammunition logistics mission has occurred at a time when almost every aspect of conventional ammunition is either being reoriented or subjected to new

and more stringent standards and guidelines. We are simultaneously coping with the effects of organizational, manpower, budgetary, and systems and procedures trauma and the effects of new concepts, standards, and guidelines on how we do our job.

MODERNIZATION OF THE CONVENTIONAL AMMUNITION PRODUCTION BASE

Under the Project Manager for Munitions Production Base Modernization and Expansion we are carrying out a very large program oriented at modernizing the conventional ammunition production base. A key part of this effort is modern technology designed to improve efficiency and effectiveness --- improve safety --- satisfy new and more stringent environmental safety and health standards and guidelines --- and improve quality and reliability.

CONTAINERIZATION & INSENSITIVE EXPLOSIVES THRUST

The drive towards containerization presents new challenges. Our distribution systems are being modernized at our production plants, depots, and ports. Land, sea, and air containerization presents a new safety problem which can be best illustrated by the fact that in the past, the holds in a break bulk ship which served as barriers simply do not exist in a container ship. Separation is a thin layer of aluminum. The probability of propagation is significantly increased and so we have a new thrust in insensitive explosives. I recently spoke to a US Department of Defense and Department of Energy Task Force which has been given the job of coming up with insensitive explosives. This is getting intense attention.

NEW OR MORE STRINGENT EPA-OSHA-SECURITY STANDARDS AND GUIDELINES

Not only are we engaged in meeting new or more stringent standards and guidelines for environmental, occupational safety and health, but security as well. The budgetary and operational implications of this are far greater than are generally recognized in the defense community as a whole. I am, therefore, pleased to have the opportunity to talk about what this means in terms of dollars and operational impact. We are programming $316 million for security --- $907 million for environmental protection --- and $73 million for occupational safety and health ($1.396 billion) in my Command. The new US Environmental Protection Agency hazardous waste and solid waste disposal regulations are under intense review and comment by a joint Service group called the Joint Conventional Ammunition Program Coordinating Group which I head. When that Group received the evaluation of the two draft EPA regulations last February, it became apparent that the practice which had been pursued in the US conventional ammunition logisitcs community from its inception could probably not be sustained in the future because of the costs associated with meeting the new standards and guidelines.

SM DEMILITARIZATION AND DISPOSAL FACILITIES STUDY

Recently I launched a study in conjunction with the US Army Depot Systems Command to review and evaluate the problem in-depth. The report was completed this month. There are clear

indications that we must reorient our thinking in the direction of regional ammunition demilitarization and disposal facilities. We simply can't afford the cost of bringing 15 or more installations into compliance. In truth, we have already done this in the chemical toxic munition and bulk agent area where we have two "regional" demilitarization and disposal facilities (Rocky Mountain Arsenal and Tooele Army Depot).

WESTERN AREA DEMILITARIZATION FACILITY

Prior to the establishment of the DoD Single Manager mission, the Navy launched a project to create a western area demilitarization facility for Navy ammunition at what was then Hawthorne Naval Ammunition Depot and is now Hawthorne Army Ammunition Plant in central Nevada. That project will be completed next year after it has been safety certified by the US Department of Defense Explosive Safety Board and the state and Federal environmental protection agencies and proved out. At that time it will be transferred from the Navy to the DoD Single Manager. Some modifications will occur after that transfer to accommodate Army, Air Force, and Marine Corps ammunition in demilitarization accounts at storage locations in the western United States. And so we have "legs up" in getting on with a regional concept. Having said all of this by way of introduction, I would like to talk more specifically about the DoD Single Manager operation.

Chart 2 - The Single Manager Mission

The Secretary of Defense has designated the Secretary of the Army as Single Manager for Wholesale Conventional Ammunition. I perform that mission by delegation from the Secretary of the Army.

The DoD Single Manager performs the full-scale procurement and production mission for the items which have been assigned to him in his Charter after the Military Services have completed their development, engineering, test, evaluation and acceptance for Service use. The Services retain their R&D missions.

The SM is the DoD Wholesale Supply Manager for assigned ammunition --- retail supply management has been left with the Military Services. The Military Services also retain the responsibility for determining requirements, planning, programming, budgeting and funding for maintenance programs in the wholesale inventory which the Single Manager executes. The SM is the DoD Manager of ammunition demilitarization and disposal, not only for SM items, but non-SM items that are located in wholesale storage facilities in the United States.

There are two stated objectives in the SM Charter --- eliminate overlap and duplication --- and achieve efficiency and effectiveness. When the Secretary of Defense made his Program Budget Decision (83) in November 1977, he assigned three targets to the SM. We have met the first two. The third target for fiscal year 1979 has been overtaken by resource cuts during the first year's operation and additional cuts targeted during fiscal year 1979.

Chart 2 - The Single Manager Mission (contd)

When the Deputy Secretary of Defense approved our SM Implementation Plan on 7 September 1976, he announced that the SM Charter should be revised, and that a second phase implementation was targeted for 1 October 1979.

Let's look at the conventional ammunition items the SM manages.

Chart 3 - Conventional Ammunition Items Assigned to the Single Manager

Shown here are the conventional ammunition items assigned to the DoD Single Manager. As most of you know, we separate ammunition into several broad categories such as "conventional" -- "chemical, toxic and non-toxic" --- "nuclear" --- and "missiles and large rockets." Of these four categories, the first two are included on this list with the exception of cartridge and propellant actuated devices and nuclear training ammunition.

Chart 4 - Types of Conventional Ammunition Assigned to the SM

Some of you may want to look a little closer at the kinds of ammunition items that are included in the preceding chart.

Not all conventional ammunition items came to the Single Manager.

Chart 5 - Ammunition Items Retained by the Services

These ammunition items are retained by the Services. As an aside, Army nuclear munitions and guidance kits for ammunition are assigned to me as an Army mission, not an SM mission. I should also point out that at every wholesale storage facility, you will find both the SM and non-SM items shown on the last two charts. We have developed policies and procedures to avoid "shooting ourselves in the foot when me must consider both in such areas as storage base planning.

This brings us to who does the work. There are many DoD Components involved,but my Command performs the SM functions.

Chart 6 - ARRCOM Personnel Summary

My total Military and civilian authorization is approximately 14,800 with 14,200 on board. Taken by itself, those are meaningless statistics. When you, however, contrast them with the strength of the Army, Navy, Air Force, and Marine Corps elements which were performing the missions now assigned to me at the heighth of the war in Soruheast Asea we find that there has been a dramatic, perhaps I should say radical reduction in manpower resources -- and there are no signs that the situation will get better in the future -- the forecasts are just the opposite. I am amazed to find people in OSD surprised at the fact that in the first years operation as DoD Single Manager I have had to absorb resource reductions. It is, of course, a paradox that the mission gets bigger and the resources get less. That is the challenge I face in finding ways by which I can meet the objectives issued by by the Office of the Secretary of Defense and yet accomplish this with reduced resources.

The SM operation is big business and here's why.

Chart 7 - Conventional Ammunition Wholesale Inventory and Five-Year Procurement Plan

This chart gives you the dimensions of the SM mission in terms of the current wholesale inventory managed and the planned five-year procurement program which we will manage between FY79 and FY84 to meet the requirements of each Service. Overall, this adds up to a wholesale inventory of $9 billion and a five-year procurement plan of $18.7 billion.

Our wholesale inventory is located at 15 wholesale storage points and amounts to 3.4 million short tons.

Chart 8 - CONUS Wholesale Inventory

You will note that when we combined the wholesale inventory under the Single Manager there was nearly as much tonnage in the three Navy Ammunition Depots as there was in the twelve Army Depots.

You will also note that the DoD Single Manager is managing almost 60% of the total worldwide conventional ammunition assets.

Chart 9 - Comparison of Depots in Terms of Stock Ownership

Another way of comparing the installations performing depot missions is to look at the ownership of the stock which they store. As you can readily see, the Army and the Navy Depots were engaged in supporting all Services. But not all of our stocks are serviceable.

Chart 10 - CONUS Demil Inventory

The Single Manager has the mission of demilitarizing all ammunition in wholesale storage facilities. As can be seen from this chart, the aggregate resulting from combination of the Army and Navy demil inventory is substantial --- and a matter of concern because money to demil has been scarce --- EPA disposal standards and guidelines are getting tougher --- new DoD security standards and guidelines have created increased demands for premium ammunition storage.

We are pressing for recognition of the need to fund the demil program --- we are also inaugurating programs to sell not only scrap and reclaimed materials but entire items to qualified domestic and foreign customers for demil by them.

Incidentially this tonnage is equivalent to 950 eighty-foot igloos --- the cost to demil this tonnage is estimated at $61 million.

Now where are these inventories located.

Chart 11 - Ammunition Storage Facilities

The wholesale ammunition storage facilities which fall within the US DoD Single Manager mission are geographically located in a dispersed pattern as shown on this chart.

Twelve of the ammunition depots are under the command of the US Army Depot Systems Command. Three are under my direct control because they are not only storage facilities, but production plants as well.

If I had to do it all over again, I would probably not have supported the transfer of the three Navy Ammunition Depots to the Army, but would have left them under the Navy just as the Army Depots have been left under the Army Depot Systems Command. I believe that I can exercise the necessary control of my Single Manager mission if I control the ammunition programs and funds. I certainly would not support transferring any more facilities to my Command in the future, because as you will see shortly, new EPA-OSHA-security guidelines --- which have nothing to do with the Single Manager mission per se --- have increased the cost of operating an installation very significantly.

Now I'd like to turn to our procurement and production mission and the role of industry in the SM operation.

Chart 12 - Planned FY78 Acquisition Program Placement

I present this chart to emphasize the fact that we place principal reliance on industry for production of ammunition components and end items --- either in commercially owned facilities which have Government equipment or in Government facilities operated by industry.

87% of the $1.4 billion annual acquisition (procurement) program is placed with private industry ($1.2 billion); 3% is placed with Government operation ($47.4 million).

7% of the acquisition (procurement) program ($99 million) supports quality assurance, engineering, and proof and acceptance testing. 3% ($42.4 million) is for transportation of raw, semi-finished, and finished conventional ammunition end items and components.

Let's look at this in terms of the physical base.

Chart 13 - DoD Conventional Ammunition Production Base

Of the total of 159 conventional ammunition production facilities, 155 or 97.5% are operated by industry. These facilities and lines are located in 26 States represented by 354 Congressmen and 52 Senators. 342 of the production lines (<u>88%</u>) are assigned or pending assignment to industry for operation.

Let's break this down into the specific production base sectors. Conventional ammunition production facilities are gnerally characterized by the following functions:

Metal Parts

Propellants and explosives

Load, assemble, and pack

They are also characterized by who owns them <u>and</u> who operates them.

Chart 14 - Industry Operated-Commercial Facilities

131 commercial conventional ammunition production facilities operated by industry support the US DoD Single Manager mission. These facilities represent 84% of the 97.5% operated by industry.

Industry also operates all but five of our Government-owned ammunition plants.

Chart 15 - Industry Operated Government Facilities

Twenty-four (83%) of our Government ammunition facilities are operated by industry. The Government has invested in these facilities because the military products produced are so dissimilar from commercial products that Government capital investment is required to make the operation of those facilities attractive to industry.

With the establishment of the SM mission, we assumed command of three Government operated ammunition facilities from the Navy in addition to Pine Bluff Arsenal.

Chart 16 - Government Operated Government Facilities

Five of our Government ammunition facilities are Government operated. The character of their mission was such that when they were established, a decision was made that they would be Government operated. Pine Bluff Arsenal, for instance, had a chemical toxic mission.

Each of these Government operated facilities is what is known as a multi-mission type activity. That is to say it performs production, depot, and other specialized missions.

No production base can remain viable unless it moves ahead with technological change through modernization and expansion to meet the needs of new ammunition items. Our partner and manager of this effort is the Project Manager to whom I referred earlier.

Chart 17 - Base Modernization Program

The present value of the US DoD Single Manager conventional ammunition production base is over $15 billion. Much of the base was built during World War II and is at least 45 years' old. It has been used at high peaks of production during World War II, the Korean Emergency, and more recently during the war in Southeast Asia. It has also supported a number of smaller conflicts in the Middle East. Since it was built, relatively small investments were made in modernization --- but where those investments were made, they demonstrated significant improvements not only in production, but in improved reactivation tiem.

Towards the end of the war in Southeast Asia, it became evident that there was a need to invest in modern technology and, therefore, a program was inaugurated in the early 1970's. To date, the PM has completed 168 projects at a value of almost $411 million. We have 164 projects underway at a value of approximately $1.4 billion and we have another 60 projects valued at approximately $1.4 billion in the Fiscal Year 1980-1984 timeframe. Almost all of these projects are oriented at improved safety as well as improved environmental protection, occupational safety and health, improved reliability, ets. I should add that the Project Manager's activities are scheduled to be transferred to my command control 1 October 1979.

This brings me to how we work with the other members of the ammunition community.

Chart 18 - Working Level Integration by OPR's

In each major functional area, we have identified Officers of Primary Responsibility (OPR's) who are usually Directors in each of the organizations performing a role in the execution of the Single Manager mission.

Their job is to maintain a "day-to-day" working relationship --- and to get together periodically when face-to-face contact is essential.

You will notice that the DoD Explosive Safety Board is one of the components of this working level integration, because it has a very significant role to play in conventional ammunition safety. OPR's have been working together for some time going back to the establishment of the Joint Conventional Ammunition Program Coordinating Group in the early 1970's to improve the cooperation amongst all of the ammunition logistics organizations of the Military Services. This group, in fact, has developed Joint Conventional Ammunition Policies and Procedures which formalize the coordination effort.

Now at the top we look like this.

Chart 19 - Command Level Integration

There is one thing we all learn as managers and that is close personal contact is essential to carry out any management job, and so while our working level OPR's are working together, so also are the Commanders of the orgnaizations which interface with the Single Manager mission.

When appropriate, the Flag and General Officers meet face-to-face either one-on-one or, if appropriate, as the Joint Conventional Ammunition Program Coordinating Group which I chair. The Coordinating Group currently meets at six-month intervals. In between times --- currently at monthly intervals --- we have an Operating Group which carries on face-to-face coordination and reports results to us.

Chart 19 off

IS THE US DOD SINGLE MANAGER MISSION A SUCCESS

I suppose at this point the basic question is -- "Is the Single Manager mission a success?"

If you measure it in terms of the dollar sign -- and ignore the cost impact of the three transferred Installations on the Army budget -- I would give you a modest "Yes." If you said to me, "Has the Single Manager operation met your expectations?", the answer is "No" from my parochial viewpoint.

The people who were the proponents for a Single Manager for Conventional Ammunition in the General Accounting Office (a Congressional agency) and the Office of the Secretary of Defense thought we should be able to realize enormous savings in consolidation of the conventional ammunition production base. It has not happened to any degree -- yet.

By one of those curious flukes, certain elements of OSD have directed the establishment of initial production facilities outside the existing base for new conventional ammunition items that have not yet been accepted for full-scale production. I have protested such actions. In FY79, which begins next month, I intend to aggressively pursue this situation because the DoD Directive requires me to obtain "maximum use of existing facilities."

I am heartened by the fact that the Air Force has been working with me on an initial production facility for combined munitions. We have been able to demonstrate reduced costs of between $840,000 and $2.4 million by using an existing production facility -- and which will be ready much sooner than a new initial production facility.

In the supply area, the Single Manager Charter did not streamline the supply process. Rather it made the process more complicated and less responsive. I am aggressively pursuing the modification of my Charter to streamline the process by consolidating four inventory control points into one. There is limited opportunity under the present Charter for me to improve customer response.

In the maintenance area, the Single Manager Charter now is limited to executing maintenance operations as determined by the Military Services. Each Service does its own maintenance planning, programming, budgeting, and funding. The effect is that the total maintenance operation is not optimized. While each Service can have the same item, the same location, maintenance planning for the total quantity at that site is not centrally managed. Consolidation of the planning, programming, budgeting, and funding functions under the Single Manager would make it possible to optimize that effort.

I will give you an indication of dollar savings the SM organization played a large part in achieving.

Chart 20 - First Year (FY78) Savings

I indicated earlier that OSD assigned a goal of $5.8 million in reduced transportation costs. What I did not say at that time was that the intent of that cost reduction was to "finance" costs incident to the implementation of the Single Manager mission by the Army.

As this chart demonstrates we exceeded that specified goal by a substantial margin. We have achieved other savings above those that were normally being experienced by the Army prior to the assignment of the SM mission.

If you ask the question, "would the other Services have achieved some of these savings had the SM mission not been established?" I would have to say "Yes." But the point is that we were asked to demonstrate savings being made under the SM umbrella and we have done so.

You will recall I talked about optimizing operations. I'll give you an example of what we hope to do.

Chart 21 - Opportunities for Ammunition Logistics Standardization

We often stress the need for standardization prior to and during the R&D phase of the ammunition life cycle. As this chart amply demonstrates, sometimes the standardization is less than successful.

I have been assigned a standardization role as a DoD Single Manager and in several test cases during the past year, I have gained confidence that even after items pass into the logistics system, we can continue to press forward and achieve standardization. As you might suspect from looking at this chart, here are some of the targets I am establishing to execute my standardization role. I am convinced that there is an opportunity for a big payoff.

And there are other areas we can do better as SM.

Chart 22 - Targets of Opportunity

As I see it, there are some real targets of opportunity for achieving savings and improved efficiency and effectiveness under the Single Manager concept, and that is the end to which I am dedicated in carrying out my present Charter and pursuing what I believe to be essential changes to it.

Chart 22 Off

What about the future? OSD has made tentative proposals for revision of the *SM Charter*.

Chart 23 - Fundamental Principles for Phase II

In presenting my views on the OSD proposals for Phase II, I stated four principles which I consider essential requisites.

Chart 24 - Service Views on OSD Proposals for SM Phase II

This chart summarizes areas of agreement and disagreement amongst the Military Services with respect to OSD proposals for SM Phase II issued on 2 September 1977.

Chart 25 - OSD Phase II Study Group

The Director of Land Warfare in the Office of the Under Secretary of Defense for Research and Engineering who is the OSD Action Officer on the SM mission has established a study group to review the Military Service's positions on Phase II.

Membership of the study group is shown on this chart. Representatives of each of the Services have briefed the study group on Service views. We understand the group will complete its report by the end of September 1978.

Chart 25 Off

SUMMARY

In summary, it is fair to say that we have made a start in implementing the SM concept, but we still have a long way to go in achieving the objectives stated in that Charter. There is progress everyday as people in all the DoD organizations get a better understanding of what it takes to get the SM job done collectively.

We will not achieve the objectives in the SM Charter fully until that Charter is modified to eliminate certain inefficiencies that are present in the way the conventional ammunition missions are divided in each of the major functional areas.

We have yet to see what the OSD study group on Phase II will say. Supposedly the study group will help OSD resolve the differences in Military Service viewpoints on what should be done.

The General Accounting Office, an arm of Congress, has initiated a review of the SM concept. GAO will undoubtedly review OSD's directive establishing the SM Charter against its own recommendations on an SM Charter as contained in the December 1974 GAO Report to the Congress.

Fiscal Year 1978 experience has given me a better insight into where my targets of opportunity for improvements are, and so in Fiscal Year 1979 I will be moving out in the pursuit of objectives and goals which I have identified. I interpret my responsibility as aggressively pursuing the basic objectives in the SM Charter and overcoming, one way or another, those obstacles that arise the current division of responsibilities between the Military Services and the SM or result from a lack of understanding of the SM Charter and how it fits into the overall DoD operation.

I trust that this has given you an understanding of what has happened and what will happen in the future in changing the face of conventional ammunition logistics.

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

GENERAL OBSERVATIONS

- GROWING INTEREST IN THE US DOD SINGLE MANAGER FOR CONVENTIONAL AMMUNITION OPERATION
- SM SEMINAR PARTICIPATION
- SM ACCIDENT AND INCIDENT CONTROL SYSTEMS
- NEW DIRECTIONS IN AMMUNITION LOGISTICS
- THE CONTAINERIZATION THRUST
- THE INSENSITIVE EXPLOSIVES THRUST
- NEW OR MORE STRINGENT STANDARDS AND GUIDELINES
- SM DEMILITARIZATION AND DISPOSAL FACILITIES STUDY
- WESTERN AREA DEMILITARIZATION FACILITIES

SINGLE MANAGER FOR CONVENTIONAL AMMUNITION

MISSION

- SINGLE MANAGER
  - PROCUREMENT & PRODUCTION
  - SUPPLY & MAINTENANCE/RENOVATION OF CONVENTIONAL AMMUNITION

WHY

- ELIMINATE OVERLAP AND DUPLICATION - OSD FY78 TARGET
  - IMPLEMENT PHASE I ON 1 OCTOBER 1977
- REDUCE COSTS - OSD FY78 TARGET
  - REDUCE TRANSPORTATION COSTS $5.8MILLION
- ACHIEVE EFFICIENCY AND EFFECTIVENESS - OSD FY79 TARGET
  - REDUCE MANPOWER BY 115

WHEN

PHASE I	PHASE II
OPERATIONAL	TARGET
1 OCTOBER 1977	1 OCTOBER 1979

SOURCE: DODD 5160.65 AND RELATED OSD DIRECTIVES

15 JUL 77

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

WHAT IS CONVENTIONAL AMMO?

DEPARTMENT OF DEFENSE DIRECTIVE 5160.65
PHASE I

CONVENTIONAL AMMUNITION INCLUDES

1. SMALL ARMS, MORTAR, AUTOMATIC CANNON, ARTILLERY, AND SHIP GUN AMMUNITION;
2. BOMBS (CLUSTER, FUEL AIR EXPLOSIVE, GENERAL PURPOSE, AND INCENDIARY);
3. UNGUIDED PROJECTILES AND ROCKETS;
4. CHEMICAL AMMUNITION WITH VARIOUS FILLERS (INCENDIARY, RIOT CONTROL, SMOKE, TOXIC AGENTS, BURSTER, IGNITERS, PEPTIZERS, AND THICKENERS FOR FLAME FUEL);
5. LAND MINES (GROUND-TO-GROUND AND AIR-TO-GROUND DELIVERED);
6. DEMOLITION MATERIAL;
7. GRENADES;
8. FLARES AND PYROTECHNICS; AND
9. ALL ITEMS INCLUDED IN THE FOREGOING, SUCH AS EXPLOSIVES, PROPELLANTS, CHEMICAL AGENTS, CARTRIDGES, PROPELLING CHARGES, PROJECTILES, WARHEADS (WITH VARIOUS FILLERS SUCH AS HIGH EXPLOSIVE, ILLUMINATING, INCENDIARY, ANTI-MATERIEL, AND ANTI-PERSONNEL), FUZES, BOOSTERS, AND SAFE AND ARM DEVICES, IN BULK, COMBINATION, OR SEPARATELY PACKAGED ITEMS OF ISSUE FOR COMPLETE ROUND ASSEMBLY.
10. ALL RELATED ITEMS IN FSC 8140.

TYPE OF CONVENTIONAL AMMUNITION

SMALL ARMS	TANK	ARTILLERY	OTHER
CAL .22	90MM	75MM	40MM
5.56MM	105MM	105MM	60MM
7.62MM	152MM	155MM	81MM
CAL .30		165MM	90MM RR
CAL .38		175MM	106MM RR
CAL .45		*5IN./.54 CAL PROJ	4.2 INCH
CAL .50	HE	8 INCH	*5 IN./.54 CAL PROP CHG
14.5MM	HEAT		GRENADES
*20MM	ADPS		FUZES
*30MM GAU 8	TP-T		ROCKETS
	BLANK	HE	MINES
	APERS	HE ILLUM	*BIGEYE BOMB
	DS-TP	HE SMKE	*COMB EFF BOMBLETS
BALL		APERS	*MUNITION DISPERSERS
TRACER			
ARMOR PIERCING			
TRAINING			
BLANK			

*USAF/USN ITEMS

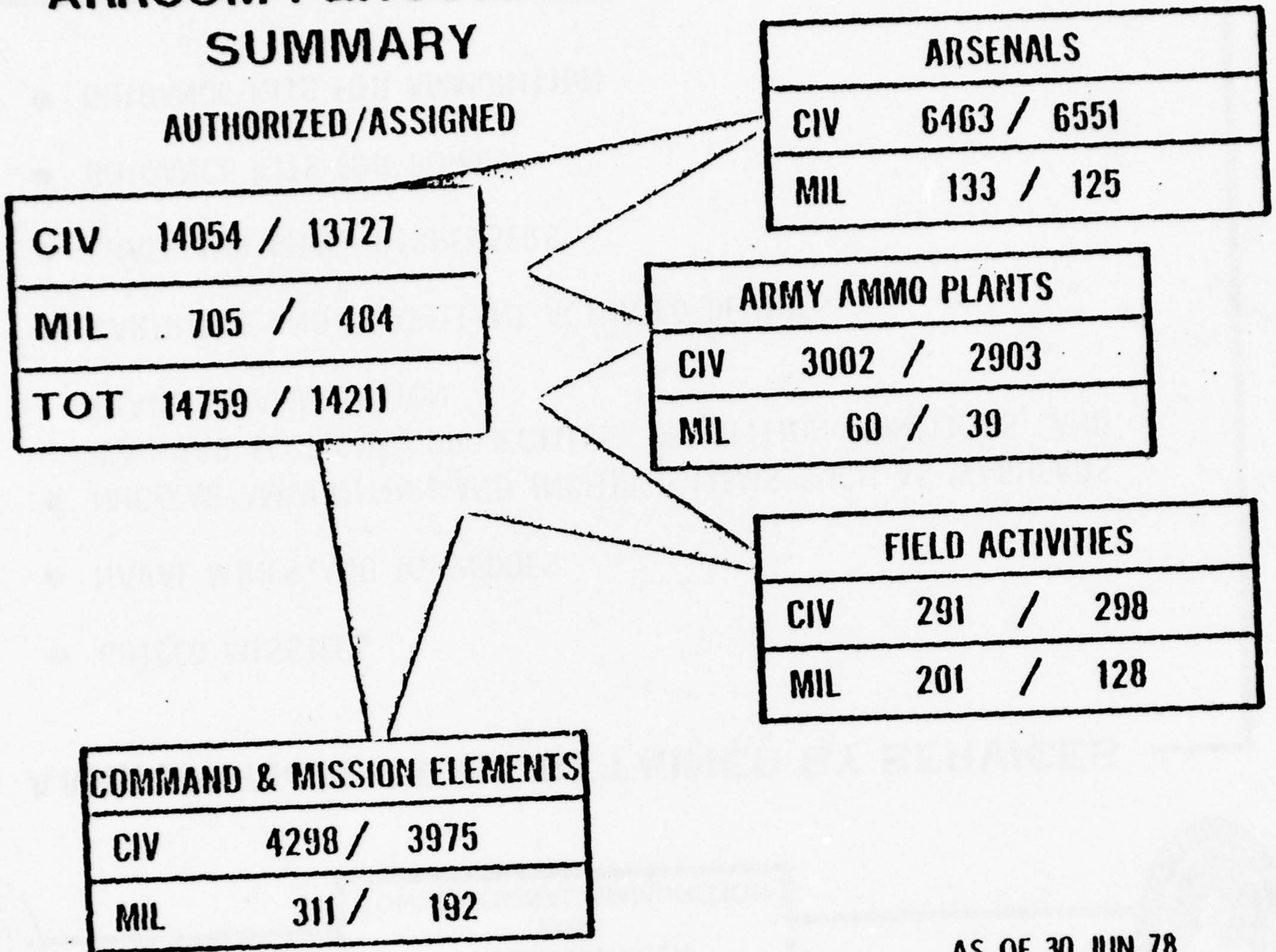
SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

AMMUNITION ITEMS RETAINED BY SERVICES

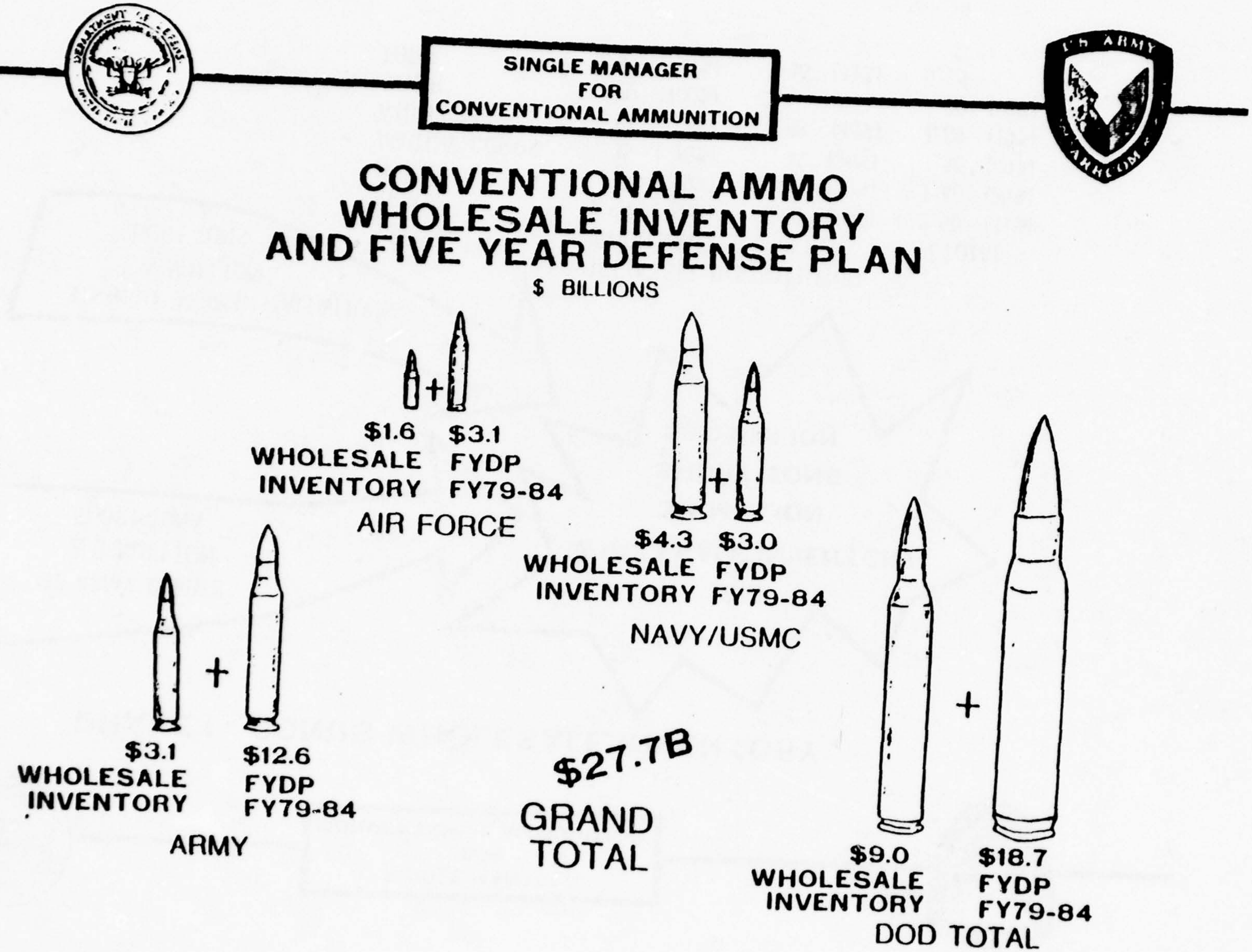
- GUIDED MISSILES
- NAVAL MINES AND TORPEDOES
- NUCLEAR AMMUNITION AND INCLUDED ITEMS SUCH AS WARHEADS, WARHEAD SECTIONS, PROJECTILES, DEMOLITION MUNITIONS, AND TRAINING AMMUNITION
- CARTRIDGE AND PROPELLANT ACTUATED DEVICES
- CHAFF AND CHAFF DISPENSERS
- GUIDANCE KITS FOR BOMBS
- GUIDANCE KITS FOR AMMUNITION

ARRCOM PERSONNEL SUMMARY

AUTHORIZED/ASSIGNED

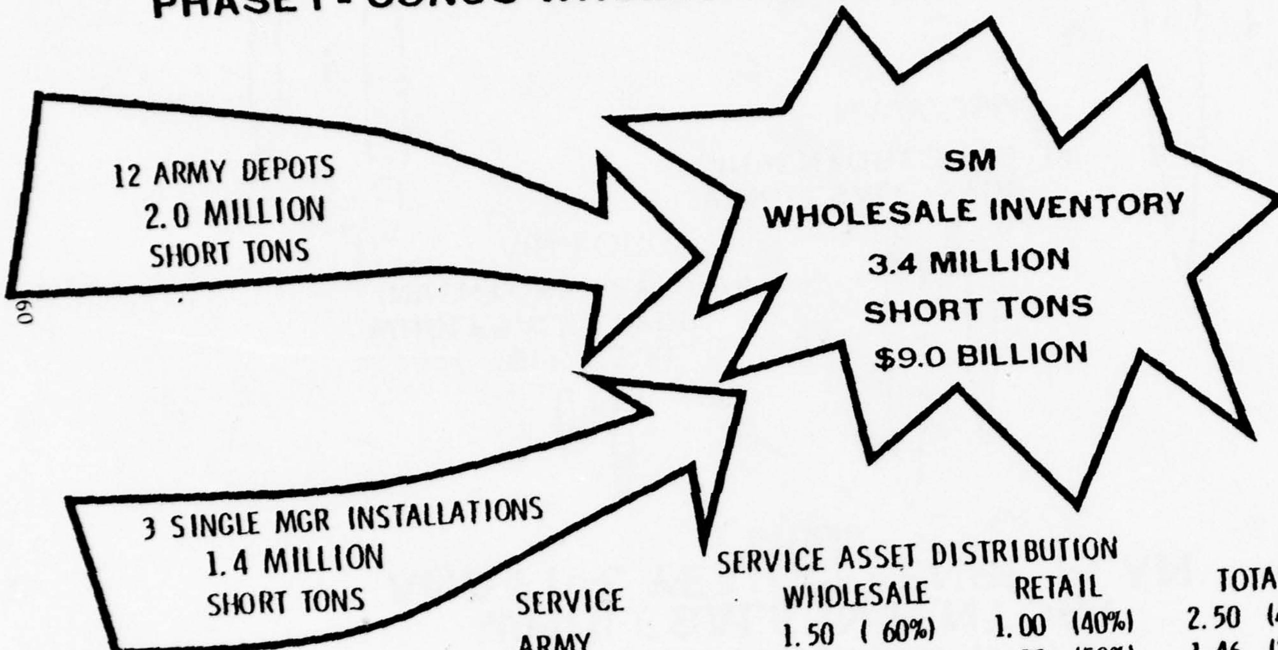


AS OF 30 JUN 78


SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION
CONVENTIONAL AMMO
WHOLESALE INVENTORY
AND FIVE YEAR DEFENSE PLAN
$ BILLIONS
$1.6
WHOLESALE
INVENTORY
$3.1
FYDP
FY79-84
AIR FORCE
$4.3
WHOLESALE
INVENTORY
$3.0
FYDP
FY79-84
NAVY/USMC
$3.1
WHOLESALE
INVENTORY
$12.6
FYDP
FY79-84
ARMY
$27.7B
GRAND
TOTAL
$9.0
WHOLESALE
INVENTORY
$18.7
FYDP
FY79-84
DOD TOTAL

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

PHASE I - CONUS WHOLESALE INVENTORY



SERVICE ASSET DISTRIBUTION

SERVICE	WHOLESALE	RETAIL	TOTAL
ARMY	1.50 (60%)	1.00 (40%)	2.50 (41%)
NAVY	.73 (50%)	.73 (50%)	1.46 (25%)
MARINE CORPS	.35 (70%)	.15 (30%)	.50 (9%)
AIR FORCE	.61 (56%)	.48 (44%)	1.09 (19%)
OTHER	.20 (100%)		.20 (3%)
TOTAL	3.39 (59%)	2.36 (41%)	5.75

5 SEP 78

SOURCE: SM HICP

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

CONVENTIONAL AMMUNITION WHOLESALE INVENTORY

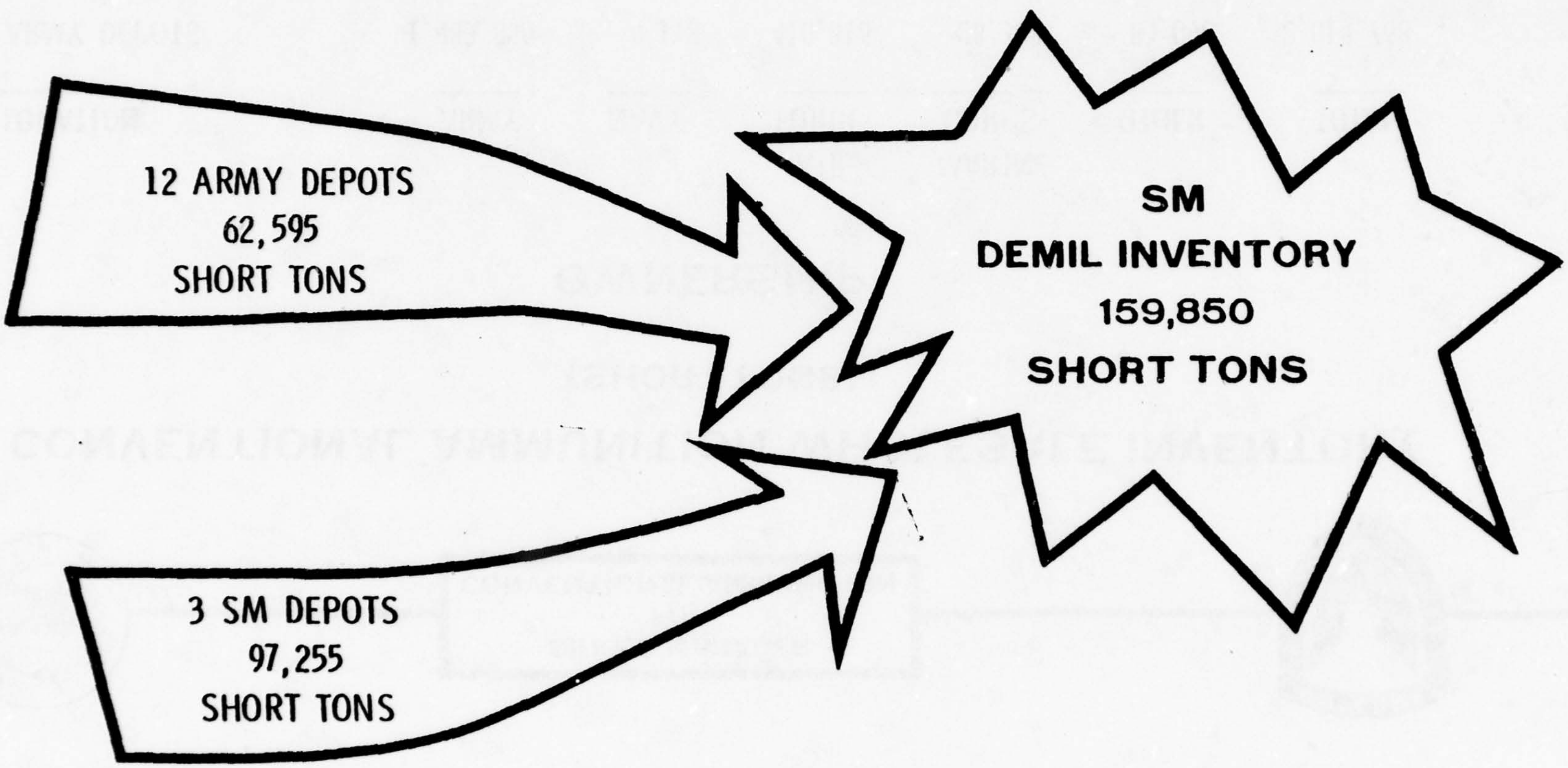
(SHORTTONS)

OWNERSHIP

LOCATION	ARMY	NAVY	AIR FORCE	MARINE CORPS	OTHER	TOTAL
ARMY DEPOTS	1,483,856	9,118	410,316	28,388	83,090	2,014,768
MC ALESTER AAP	8,117	88,913	135,675	80,427	45,532	358,664
CRANE AAA	936	158,882	15,370	71,370	33,708	280,266
HAWTHORNE AAP	6,570	473,730	46,680	167,679	37,845	732,504
TOTAL	1,499,479	730,643	608,041	347,864	200,175	3,386,202

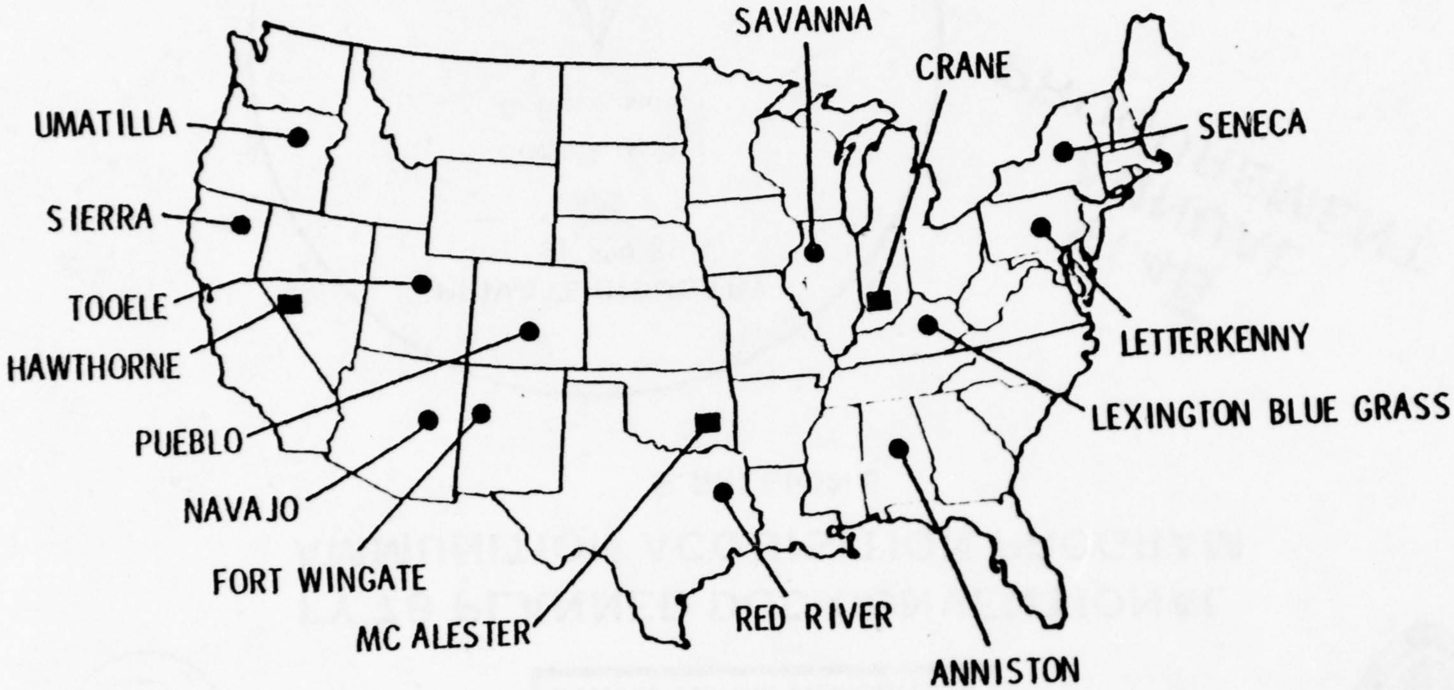
SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

PHASE I - CONUS DEMIL INVENTORY



SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

AMMUNITION STORAGE LOCATIONS



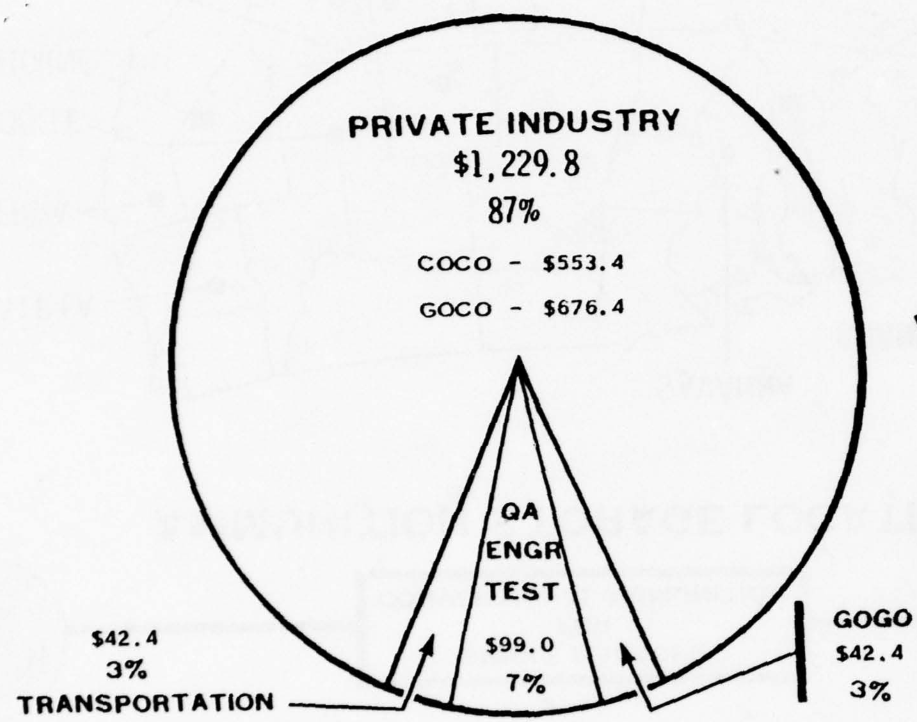
● UNDER COMMAND OF US ARMY DEPOT SYSTEMS COMMAND

■ UNDER COMMAND OF US ARMY ARMAMENT MATERIEL READINESS COMMAND

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

FY 78 PLANNED DOD CONVENTIONAL AMMUNITION ACQUISITION PROGRAM

$ MILLIONS

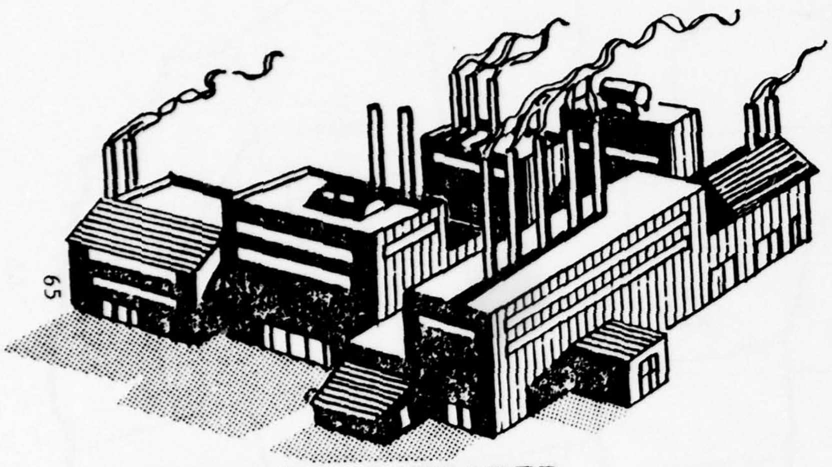


$1.4B ANNUAL PROCUREMENT

ARMY:	$904.6
NAVY:	171.9
AIR FORCE:	68.1
MARINE CORPS:	45.7
FMS:	213.6
GA/MAP:	9.7

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

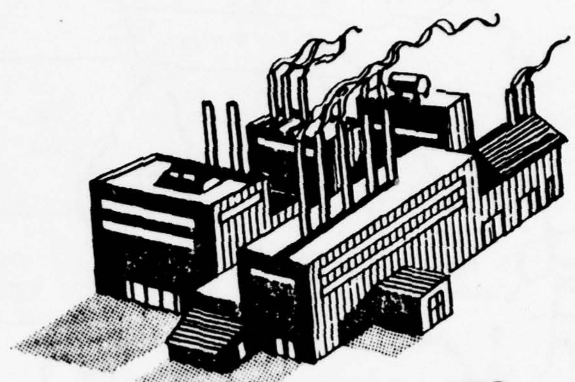
DOD CONVENTIONAL AMMUNITION PRODUCTION BASE



65

INDUSTRY OPERATED

155 FACILITIES
342 PRODUCTION LINES
$12.7 B REPLACEMENT VALUE
GOV'T INVESTMENT ONLY



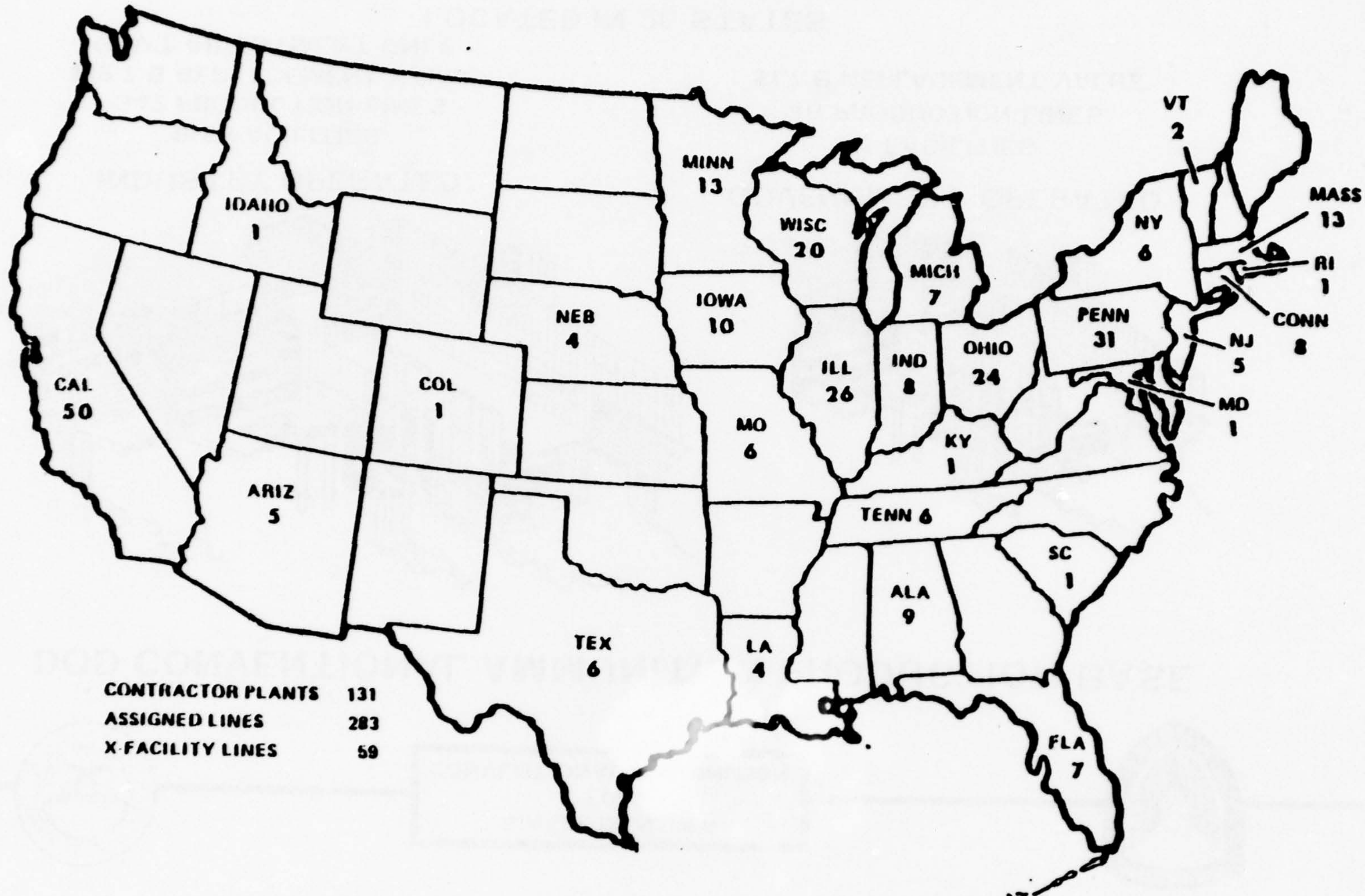
GOVERNMENT OPERATED

4 FACILITIES
46 PRODUCTION LINES
$1.7 B REPLACEMENT VALUE

**LOCATED IN 26 STATES
REPRESENTED BY
354 CONGRESSMEN AND
52 SENATORS**

DOD CONVENTIONAL AMMUNITION PRODUCTION BASE

INDUSTRY OPERATED COMMERCIAL FACILITIES WITH GOVERNMENT PEP LINES

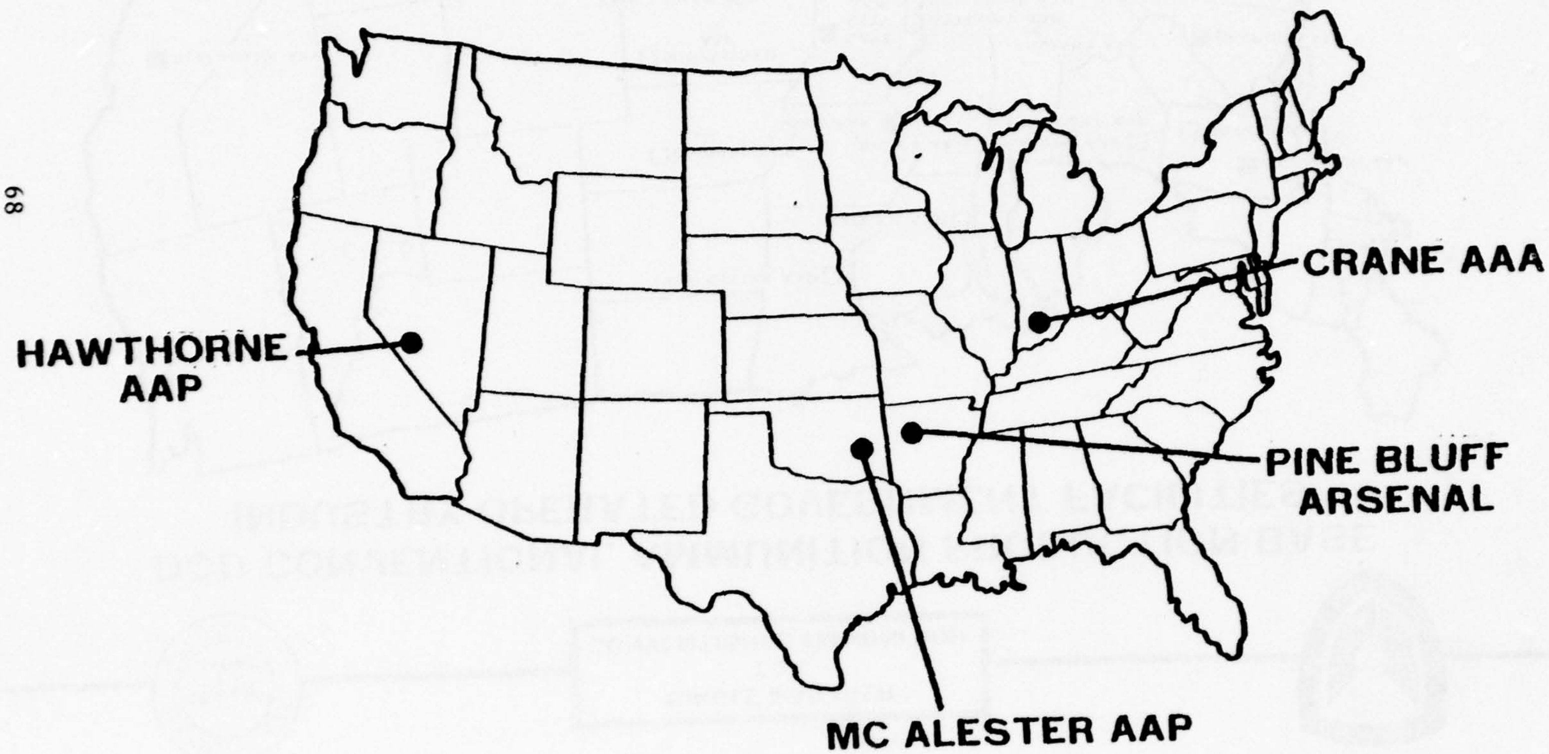


SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

DOD CONVENTIONAL AMMUNITION PRODUCTION BASE
INDUSTRY OPERATED GOVERNMENT FACILITIES

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

DOD CONVENTIONAL AMMUNITION PRODUCTION BASE
GOVERNMENT OPERATED GOVERNMENT FACILITIES



SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

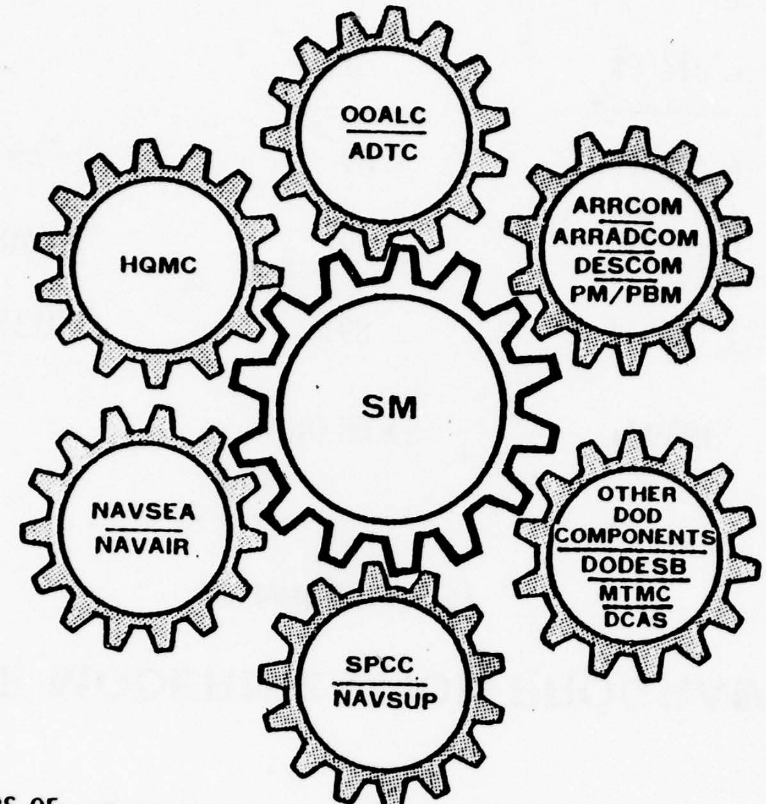
BASE MODERNIZATION PROGRAM

($ MILLIONS)

	PROJECTS	VALUE
COMPLETED	168	$ 410.7
UNDERWAY	164	1,363.6
FY 80-84	60	1,435.9
TOTAL	392	$3,210.2

SINGLE MANAGER FOR CONVENTIONAL AMMUNITION

WORKING LEVEL INTEGRATION
OFFICERS OF PRIMARY RESPONSIBILITY (OPR'S)*

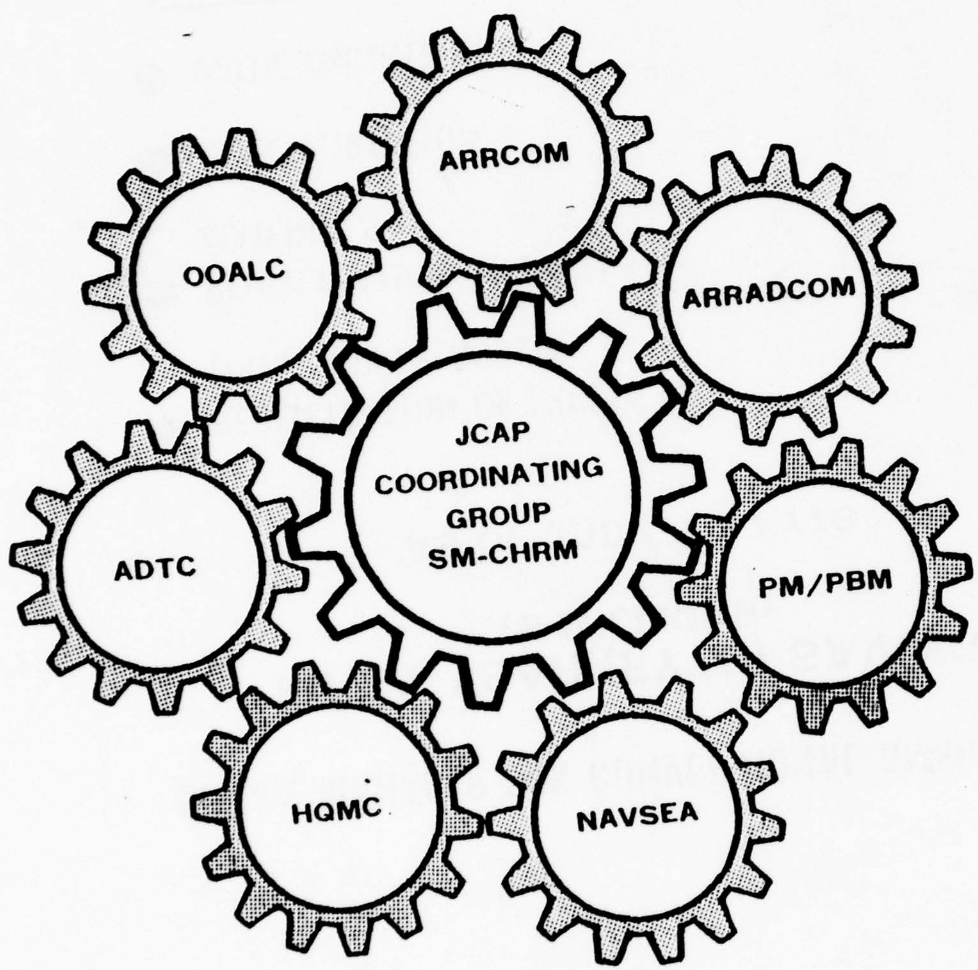


* DIRECTORS OF

- SUPPLY
- PROCUREMENT
- PRODUCTION
- MAINTENANCE
- PRODUCT ASSURANCE
- SYSTEMS MANAGEMENT
- LOGISTICS ENGINEERING
- SAFETY
- SECURITY
- MGMT INFO SYSTEMS
- SYSTEMS ANALYSIS

SINGLE MANAGER FOR CONVENTIONAL AMMUNITION

COMMAND LEVEL INTEGRATION



SINGLE MANAGER FOR CONVENTIONAL AMMUNITION

FIRST YEAR (FY78) SAVINGS
($ MILLIONS)

AS OF 3RD QTR, FY78

● REUTILIZATION OF EXCESS & LONG SUPPLY ASSETS	$25.9
● REUTILIZATION OF EXCESS MATERIALS	19.5
● TRANSPORTATION	10.5
● VALUE ENGINEERING	1.0
TOTAL	$56.9

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

PROLIFERATION OF AMMUNITION

			NSN'S PECULIAR TO ONE SERVICE			
	TOTAL NUMBER OF NSN'S	NSN'S COMMON TO TWO OR MORE SERVICES	AIR FORCE	ARMY	MARINE CORPS	NAVY
CTG .38 CAL ALL TYPES	19	(10)	(1)	(5)	(1)	(2)
CTG .50 CAL ALL TYPES	261	(67)	(23)	(130)	(3)	(38)
CTG 20MM ALL TYPES	222	(111)	(26)	(32)	(0)	(53)
CTG 40MM ALL TYPES	172	(132)	(1)	(18)	(4)	(17)

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

TARGETS OF OPPORTUNITY

RANGE OF
POTENTIAL SAVINGS
$60 - $110 MILLION

- STANDARDIZATION OF ITEMS AMONG THE SERVICES
- UTILIZATION OF CURRENT PRODUCTION CAPACITY
- AGGREGATION OF QUANTITIES
    - PRODUCTION
    - RENOVATION
    - DEMILITARIZATION
- COMMONALITY IN PACKAGING/UNITS OF ISSUE
- COST EFFECTIVE UTILIZATION OF THE TOTAL STORAGE BASE

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

FUNDAMENTAL PRINCIPLES FOR PHASE II

- WORK IN WAR AS WELL AS IN PEACE
- SM DOESN'T REQUIRE COMMAND/CONTROL OF ADDITIONAL FACILITIES
- SM AND SERVICES REQUIRE WORLDWIDE VISIBILITY OF AMMUNITION
- DEVELOP PLANS BY JOINT SERVICE TEAM

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

OSD DRAFT PROPOSED GUIDANCE- SM PHASE II

- SERVICE AGREEMENTS
  - EXCLUDE NAVAL MINES, DEPTH CHARGES, AND TORPEDOES; GUIDANCE KITS; SWIMMER WEAPONS; CHAFF WARHEADS; EOD TOOLS AND EQUIPMENT; CAD/PAD; AND NUCLEAR MUNITIONS FROM SM ASSIGNMENT.
  - USE JOINT TRANSITIONING POLICIES AND PROCEDURES ESTABLISHED FOR PHASE I
  - DO NOT EXTEND SM ROLE INTO THEATERS OF OPERATION
  - DELETE CONVERSION OF GOGO FACILITIES TO GOCO
  - ISSUE A MANUAL OF JOINT POLICIES AND PROCEDURES IMPLEMENTING THE OSD SM DIRECTIVE
  - USE SERVICE AUDIT AGENCIES TO VALIDATE RESOURCES
- SERVICE DISAGREEMENTS
  - ESTABLISHMENT OF A DEFENSE NICP AND NMP
  - RELEASE DATE OF SERVICE AMMUNITION PROCUREMENT PROGRAM TO THE SM
  - SM PHASE II RESOURCE REQUIREMENTS

* ASA (RDA) MEMORANDUM, SUBJECT: SM PHASE II RESPONSIBILITIES, 25 JANUARY 1978

SINGLE MANAGER
FOR
CONVENTIONAL AMMUNITION

SINGLE MANAGER

SM PHASE II - OSD STUDY GROUP

- OSD STUDY GROUP MEMBERSHIP

  MR. ALEXANDER, RAND CORP (LEADER)
  MG L. E. VANBUSKIRK, USA (RET)
  MR. R. J. HAMMOND, STETTER CORP
  MR. JOSEPH PALUSACK, USN (RET)
  MR. DONALD WHITE, NORRIS INDUSTRIES (RET)
  MR. JOSEPH BROWNING, USN (RET)

- COMPLETION - 30 SEPTEMBER 1978

THE FOLLOWING PAGES INCLUDE THE FOUR TOPICS PRESENTED BY THE DEFENSE LOGISTICS AGENCY CONTRACT ADMINISTRATION SERVICES PANEL UNDER THE HEADING:

SAFETY REQUIREMENTS FOR CONTRACT BIDS

COPIES OF THE DLA EXPLOSIVES SAFETY AND INDUSTRIAL SAFETY CERTIFICATION PROGRAMS MAY BE OBTAINED BY WRITING TO:

DLA - DQMSO
805 Walker Street
Marietta, Georgia 30060

TOPIC: AN OVERVIEW OF CONTRACT ADMINISTRATION AND THE ROLE OF THE DLA SPECIALIZED SAFETY PROGRAM IN CONTRACT ADMINISTRATION

PREPARED BY: RAYMOND J. FATZ, Safety Specialist
DCASMA Syracuse

Administration of defense contracts placed with commercial suppliers covering items ordered for the military services is a major function of DLA, and is performed by the Defense Contract Administration Services (DCAS) through a nationwide network of regional, management area and plant representative offices.

The role of contract administration in the Department of Defense is to assure that Defense contractors comply with contract requirements and to assist purchasing offices in handling problems connected with these contracts.

DCAS assists procuring agencies in obtaining from industry the products and services for which they have contracted. DCAS works to assure that these products and services are delivered when and where needed at the agreed upon price, and that they are of satisfactory quality.

DCAS services are channeled through its nationwide organization of civilian and military personnel located where industries are concentrated throughout the United States. DCAS is divided into nine regions. These regions are sub-divided into 49 DCAS Management Areas (DCASMAs) and 30 DCAS Plant Representative Offices (DCASPROs). Plant Representative Offices administer contracts at a specific contractor plant while management area offices handle contracts within a given geographical area.

Contract administration services are performed at or near contractor plants to minimize problems of contract performance and to assure compliance with the terms and conditions of government contracts.

The DLA quality assurance organization is responsible for assuring contractors furnishing supplies and equipment to the military services meet all specification and contractual requirements.

A unique mission of Quality Assurance is its Specialized Safety Operations. Specialized safety personnel assist contractors in complying with contract safety clauses, thereby assuring contract completion without interruption due to mishaps or damage to government property.

The DLA Specialized Safety Program provides a means to determine the adequacy and effectiveness of a contractor's accident prevention program as it pertains to DCAS administered contracts.

The primary standards used by Specialized Safety personnel in conducting surveys at ammunition and explosives plants is the DoD Contractor's Safety Manual for Ammunition, Explosives and Related Dangerous Materials - DoD 4145.26M.

Procurement of ammunition or explosives will contain the mandatory Defense Acquisition Regulation (DAR) Clause 7-104.79 which requires compliance with DoD 4145.26M. DARs were formerly known as ASPRs - Armed Services Procurement Regulations.

The Manual provides uniform safety principles to be used by contractors for all work performed in connection with DoD contracts involving ammunition and explosives.

The Manual also prescribes safe standards for insuring continuity of production safeguarding personnel, and preventing property damage at contractor operated plants.

The Safety requirements of DoD 4145.26M are to be applied to all contracts involving ammunition or explosives. To accomplish this policy, all solicitations and resulting contracts involving the development, testing, storage, manufacture, modification, renovation, demilitarization, packaging, transportation, handling, disposal, inspection, repair or other use of ammunition and explosives will include the clause set forth in DAR 7-104.79.

The clause is not to be included in contracts solely because of

1. Inert ammunition components containing no explosives, active chemicals or pyrotechnics, or

2. Flammable liquids, acids or other chemicals having fire or explosive characteristics unless such chemicals are intended for initiation, propulsion or detonation as an integral or component part of an ammunition or explosive end item or weapon system.

Neither the requirements of this clause nor any act or failure to act by the Government in surveillance or enforcement thereof shall affect or relieve the Contractor of responsibility for the safety of his personnel and his property and for the safety of the general public in connection with the performance of the contract, or impose or add to any liability of the Government for such safety.

The Contractor is not entitled to rely on the requirements of the manual or any Government surveillance, or lack thereof, in discharging his safety responsibility.

Both parties - the Contractor and the Government - have certain obligations and responsibilities which must be recognized prior to, and after a contract is awarded.

a. The procuring Contracting Officer (PCO) is responsible for:

(1) Providing safety clauses and technical safety data in contracts.

(2) Seeking counsel or advice of the cognizant DoD component safety staff to insure that adequate safety criteria is included in the contract.

(3) Having pre-award safety surveys conducted to determine that the contractors can meet the applicable criteria.

(4) Evaluating conditions found during pre-award surveys of contractors plants. When the applicable safety criteria cannot be met, amend the contract to reflect the authorized waivers or exemptions.

(5) Requiring the contractor to provide site and construction plans for review.

(6) Taking appropriate action on safety matters reported by the Administrative Contracting Officer (ACO).

b. The Contractor is responsible for:

(1) Complying with the terms of the contract.

(2) Submitting to the ACO requests for waivers or exemptions when he cannot comply with the terms of the contract.

(3) Developing and submitting site plans.

(4) Developing and implementing a safety program.

(5) Designating a responsible individual to administer the safety program.

(6) Notifying the Contracting Officer immediately after a mishap involving ammunition or explosives.

(7) Conducting an investigation of the accident or incident and submitting a report to the Contracting Officer.

(8) Inserting the substance of DAR Clause 7-104.79 in every applicable subcontract which involves ammunition and explosives.

DLA furnishes a complete range of contract administrative services to the Department of Defense, to other Federal agencies and foreign governments.

These services begin with pre-award surveys to determine the capabilities of prospective contractors.

The Agency then carries through, the complicated business of getting the job done efficiently and in compliance with the contract and regulations.

A pre-award safety survey is an onsite evaluation by Specialized Safety personnel of a prospective contractor's capability to perform under the safety requirements of the bid package.

If the proposed procurement for ammunition or explosives does not contain the safety requirements of DAR 7-104.79, Specialized Safety personnel will advise the pre-award monitor that the safety portion of the pre-award survey cannot be performed as the proposed procurement package is in violation of DAR 1-323 which requires that DAR 7-104.79 be included in all procurement for ammunition and explosives.

The prospective contractor's ability or inability to comply or gain compliance with the applicable mandatory safety provisions of DoD

4145.26M will be specifically stated in the pre-award safety survey report prepared by specialized safety personnel.

When mandatory requirements of the Manual (DoD 4145.26M) are to be waived prior to award, the specific requirements to be waived must be set forth in the solicitation or by modification. Care must be taken to assure that the waivers granted are compatible with sound safety principles.

The pre-award safety survey report will contain specific recommendations in order for the Procuring Contracting Officer to exercise the options of award, no award, resurvey, or survey of proposed subcontractor.

Pre-award safety survey reports will reflect specific paragraph references to standards violated, and the actions the contractor indicated he will take to correct the deficiency if awarded the contract.

For pre-award surveys involving explosives subcontracting, the Safety Specialist conducting the pre-award safety survey of the proposed prime contractor must assure that DAR 7-104.79 and all other specific safety data will be included by the prime contractor in the subcontract, and that the proposed subcontractor can meet the contractual safety requirements appropriate to his subcontracted item. These requirements will involve such tasks as obtaining explosives handling licenses and preparing standing operating procedures.

If safety clauses in proposed subcontracts are found to be inadequate or nonexistent, a request is made to the prime contractor to include required safety clauses in the purchase order or subcontract.

It will be the responsibility of the proposed prime contractor to furnish Specialized Safety personnel a copy of all necessary documentation on the proposed subcontractor's safety posture. The documentation will include as much of the following as possible and be included in the pre-award safety survey report:

(1) A site plan with an accurate scale or indicated distances showing all related buildings (intraline and inhabited), plant boundary, and nearest railroad, highway, within the corresponding quantity - distance.

(2) Safety Program, organization, and training.

(3) Personnel and explosives limits for each building.

(4) Hazard class for explosives in each building.

(5) Types of operations in each building, and a sampling of Standard Operating Procedures.

(6) Types of construction of each building (including interior surfaces).

(7) Types of facilities/utilities servicing each building.

(8) Fire protection.

(9) Personal protective equipment.

(10) Operational shielding.

(11) Grounding and bonding.

(12) Accident history.

(13) Current waivers or exemption in force.

If satisfactory documentation and descriptive assurance is not provided by the prime contractor for his proposed subcontractor, a recommendation of no award will be submitted to the pre-award monitor. However, in lieu of the foregoing, the pre-award monitor or the PCO may be requested to have an onsite safety survey conducted at the proposed subcontractor's facility.

Since more than half of the dollar value of Defense prime contracts are subcontracted, a lot of time and money can be saved if the prime contractors insure that their subcontractors can meet contractual safety requirements.

After the pre-award process is completed and a contractor is selected, a post-award conference is conducted to assure that all matters between the contractor and Government requiring clarification or resolution are considered and contractual requirements explained.

At the post-award conference specialized safety personnel will review all site plans, operating procedures, and safety surveys submitted during the pre-award phase to insure that no changes have been made that may adversely affect contract safety requirements.

A new ammunition/explosives contractor will be given an initial survey prior to the beginning of significant production. Additionally, contractor facilities will be surveyed at least quarterly to assure compliance with contractual safety requirements, assure the safety of Government personnel and property, and prevent accidents which would adversely affect completion of Government contracts.

Prime Contractor - Subcontractor Interface

The Prime contractor is responsible for assuring that all supplies and services procured from his suppliers (subcontractors and vendors) conform to the contract requirements.

The selection of sources and the nature and extent of control exercised by the contractor should be dependent upon the type of supplies and his suppliers demonstrated capability to perform.

The Prime contractor should have a method of controlling his subcontractors and a means of evaluating the effectiveness of these controls.

To assure an adequate and economical control of subcontractors, the contractor's responsibility for the control of purchases includes the establishment of a procedure for:

(1) The selection of qualified suppliers.

(2) The transmission of applicable requirements in the Government contracts.

(3) The evaluation of the adequacy of procured items.

(4) Effective provisions for correction of nonconformances.

Surveillance by Specialized Safety personnel at subcontractor's facilities does not relieve the Prime Contractor of his responsibilities. It is important for the Prime Contractor to maintain visibility of cognizant subcontractors.

By insuring that subcontractors do meet all the requirements for performing work on government ammunition and explosives contracts, the contractor can realize:

Timely completion of the contract, and

No additional cost.

TOPIC: SPECIALIZED SAFETY IN THE PREAWARD SURVEY

Lawrence Del Regno, Safety Manager, DCASR Dallas

For the next fifteen minutes, we're going to discuss the safety segment of the preaward survey for ammunition or explosive
Slide #1 materials procurements. Authority for preaward surveys is contained in DAR 1-905.4 which requires, among other things, that the preaward evaluation "may be accomplished by use of ...... an onsite inspection of plant and facilities to be used for performance on the proposed contract." Further, paragraph K-201(c) in Appendix "K" of the DAR requires purchasing offices to forward preaward requests to the appropriate cognizant Contract Administration Service component, as listed in DoD Handbook 4105.59H. Accordingly, the implementation of these references usually means that a DLA component will be performing the preaward safety survey, and that this survey will, with very few exceptions, involve an onsite inspection of plant and facilities as prescribed in the DAR. As you know, the contract award is not always made to the lowest bidder. Frequently, other considerations, specifically including safety, may override cost considerations. In order to make an intelligent decision, the PCO has the right to expect accurate, objective information on which to base a judgment for contract award. Our purpose today then is to review the information the proposed contractor should be prepared to furnish the evaluator in order to facilitate the completion of the survey, while at the same time enhancing his own prospects for eventual award. Certainly, if the prospective contractor knows in advance the type, scope, and depth of the information required, he can assure himself of a fair and equitable evaluation.

The U. S. Army has been designated the single service manager for conventional ammunition, and as such, is responsible for the procurement of conventional ammunition for all DoD components. There are some exceptions: items of central interest or peculiarity to an individual service may continue to be purchased by that service. For example, the Navy will probably continue to purchase torpedoes for its submarines.

Accordingly, we will devote our time to a review of the Army's safety requirements for conventional ammunition and explosives preaward evaluations. These are listed in Appendix "C" of ARMCOM Supplement #1 to DARCOMR 385-17, and are incorporated in a form
Slide #2 DRDAR SF Form 407, which is used by the preaward evaluator (who will usually be the Contract Administration Services safety specialist) in preparing his report to the Army Purchasing Agency.

The form contains 24 headings or areas of inquiry, and as you can imagine, a considerable amount of detail is required. The

evaluator normally secures most of the information through observation and his own investigative techniques. However, a considerable amount of data must come from the bidder. Normally, the CAS element is allowed seven working days to complete and forward the preaward survey to the buying agency. Depending upon the size and complexity of the procurement, seven days is not a lot of time in which to complete the survey, and any assistance that can be furnished by the bidder will help to assure himself of a fair, thorough evaluation. The form contains many data items that can only be furnished by the prospective contractor, and we'll discuss them now.

Slide #3 First of all, as required by DAR 7-104.79a, the preaward survey uses DoD Manual 4145.26M as the basic reference. Where the DoD Manual is silent on a subject, DARCOMR 385-100 (formerly referred to as AMCR 385-100) is cited as the authority. Additionally, the bid packages normally will contain a number of major component safety data statements, which will describe specific hazards and test data on materials involved in the procurement. These statements may come in the form of standard sheets or aperture cards. We will discuss them in more detail later, but it is important to note at this point that the information contained in these data sheets should be carefully reviewed and incorporated into the contractor's production plan which is to be presented to the preaward team.

Slide #4

Slide #5 Item A does not refer to the U. S. Treasury's Alcohol, Tobacco, and Firearms License. If the bidder is working inside the limits of an incorporated community, a copy of a license or written permission authorizing the company to handle explosive materials and which specifies weight limits, is vital. If the community does not require licensing, then the prospective contractor will be expected to furnish a written statement to that effect over the signature of a company official with signatory authority. The same rules apply for facilities located <u>outside</u> incorporated communities; a state license or written statement by the bidder is required.

Slide #6 The organization chart required by paragraph B must show the individual responsible for safety somewhere on the chart, and preferably, he should be identified by name, just as he is on the front page of the report. Remember, DoD Manual 4145.26M (paragraph 103d(5)) requires the contractor to designate "a responsible individual to administer the safety program."

Slide #7 There may be a considerable amount of material required to satisfy the requirement of Item C. At a minimum, a written general safety plan or program which encompasses general plant

operations is required. It may, but does not have to, address itself to the specific safety measures necessary for the procurement involved in the preaward survey. These procedures are required separately under another section of the form, which we will discuss later. The master or general program should include an explanation of its implementations; this is probably best illustrated by means of a safety organization chart which would show the level and scope of safety responsibility at each level of production. Either method, by written instructions or chart, is acceptable,

Slide #8

of course, as long as responsibilities are clearly fixed. The program must also include a plan for training of work personnel which at a minimum should include:

a. Safety orientation and supervised on-the-job training of new hires.

b. A training plan for on-the-job station supervised training of work personnel involved in work unfamiliar to them.

c. A program of continuing instruction in safety procedures and safety awareness.

Slide #9

And finally, the bidder is expected to furnish the evaluator a short resume of the safety director's training, education, and experience in the explosive safety field.

Slide #10

The plant map may be as simple or complex as the bidder wishes. It may be large, in blueprint style, or it may be shown on 8 x 10½ plain paper. There are several components that should be shown: the distance from the plant boundary to public roads, the distance to railroads, and finally, the distance to inhabited buildings. And, of course, there should be identifying information on the drawing including a scale, north arrow, town names, road identification, etc.

Slide #11

If the bidder plans to produce hazardous components of the article in procurement at more than one location, or if he plans to subcontract any hazardous work to another company, he should be prepared to furnish the evaluator the name, address, and telephone number of these activities. The Army requires a preaward safety survey of all contractor elements producing hazardous components for the procurement.

Slide #12

A simple listing of contracts currently in work is all that is required here. The contract number, the buying agency, the item

Slide #13

involved, and the building or buildings in which the items are being produced should be included. This chart (#13) shows an example of what might be submitted. This information is important to the evaluator in judging the compatability of operations within the plant.

Obtaining information required by Items G, concerning personnel strength; H, which involves construction features and condition of the buildings to be involved in the procurement; and Item I, which concerns an evaluation of electrical equipment and wiring, are all the function and responsibility of the evaluator. We won't devote any time to these subjects now, except to note that the bidder should be prepared to discuss building and electrical features of his production area.

Slide #14

The evaluator will physically determine the effectiveness and the integrity of the bonding and grounding systems. The bidder should be prepared, however, to furnish for the evaluator's inspection, the record of grounding and conductive floor tests performed at the plant.

Slide #15

Note that in the case of lightning protection, the form shows a reference in parenthesis to DARCOMR 385-100. Apparently, this is because paragraph 504 of DoD Manual 4145.26M is not as comprehensive in its requirements as Chapter 8 of DARCOMR 385-100. You will find too, that the DARCOMR regulation standards exceed, in some aspects, those of the NFPA Lightning Protection Code (NFPA #78), which is cited in DoD 4145.26M. Which reference is applied will depend, of course, on what is written in the contract. Paragraph 504 of DoD 4145.26M permits installation "in accordance with requirements of the cognizant DoD components." There are two significant contributions to be made by the contractor in satisfying the preaward survey: one is a record of tests of the lightning protection system, a requirement similar to that for bonding and grounding tests noted earlier, and the other is the development of written procedures for shutdown of the plant, and evacuation of personnel during electrical storms. These procedures may, of course, be appended to the general safety program that was discussed earlier, but the manual requires that electrical storm evacuation be a separate operating procedure.

Slide #16

The evaluator will secure by observation or questioning the information required by Item L, Industrial Safety Practices; M. Protective Clothing and Equipment; N, Health Services; O, Health Hazards; and most of Item P, excepting those items shown on the screen where information must be secured from the bidder. As in the case for

electrical storm procedures, the bidder is required by the manual to develop separate fire plans which provide for warning, alarms, evacuation, fire prevention and protection, etc. The plan should include information on the organization and training of plant fire brigades, training for the personnel involved, ahd the brigade's interface with professional fire fighting organizations. Additionally, the evaluator will require a copy of a mutual assistance agreement with city, county, state, or commercial fire fighting organizations when the bidder is located outside of an incorporated community.

Slide #17 The bidder will be expected to furnish the evaluator a drawing showing the QD hazard zones for each hazard unit in the plant. The amount of detail necessary is predicated upon the number and type of buildings in the plant, dividing walls, similarity of

Slide #18 hazards, etc. The slide shows a very simple drawing which shows building or cellular QD hazard and load limits and their related intraline and inhabited building hazard arcs. The evaluator will

Slide #19 use this drawing in conjunction with the area drawing which was discussed earlier, to reach his conclusions concerning QD criteria. Compatibility of materials both in storage and in work will be determined by observation by the evaluator.

Slide #20 The SOPs involved in Item S are those relating to work station procedures. Ideally, a station SOP should describe the task to be performed, and the safety precautions necessary for the operations. It should be tailored to the specific work station for a specific product; the amount of detail will depend upon the complexity of the operation, and the skill and experience of the operators. The SOP is approved by responsible individuals, including

Slide #21 the safety director before it is posted for use at the station. The slide shows an example of a station SOP. SOPs may, at the option of the contractor, also include photographs or drawings to be posted at the work station, illustrating unsafe conditions which could arise at the station, including related instructions to the operator.

Slide #22 The evaluator will fulfill requirements of Item T, transportation, by observation and questioning.

Slide #23 Item U contains a long list of plant operations which are examined by the evaluator. To satisfy one of the requirements, the bidder is expected to furnish a drawing of the layout of operations. This can be a very simple line drawing showing the sequence of production, with each station shown on the drawing coordinated with the same station described in the work station SOP described earlier.

Slide #24 Two things may be required when the contract calls for the contractor to perform tests: a testing SOP which contains each of the elements shown on the slide, and written FAA clearance of tests involving airspace. The evaluator will, of course, inspect the effectiveness of the personnel shelters, down range fans and clearances, warning equipment, etc.

Slide #25 Decontamination and collection and disposal procedures can be a part of a general safety program when dealing with general rules involving these subjects. For example, subjects like the marking of containers to assure proper segregation of wastes, location of burning sites, pickup times, etc. all lend themselves to a set of general rules. However, it is essential that a separate SOP or segment of an SOP be devoted to the safe handling of each explosive item when it becomes a candidate for destruction. The operators should have these instructions with them, and they should be available for the preaward survey evaluator's appraisal.

Slide #26 Slide #27 The final item for appraisal is the subject of Special Survey Requirements. Ordinarily, these are contained in Major Component Safety Data Statements. As mentioned earlier, it is important for the contractor to review these data statements carefully; these statements normally constitute an amendment to the safety DAR, because they may contain handling requirements for a particular item that exceed the standards contained in either DoD Manual 4145.26M or DARCOMR 385-100, and, of course, failure to take these limitations into account may seriously affect the plan for production that the bidder submits to the evaluator.

I hope that this presentation has been helpful to you. Do you anticipate any problems with preaward preparations that you would like to discuss at this time?

1-905.4 *Pre-Award Surveys.*

(a) *General.* A pre-award survey is an evaluation by a contract administration office of a prospective contractor's capability to perform under the terms of a proposed contract. Such evaluation shall be used by the contracting officer in determining the prospective contractor's responsibility. The evaluation may be accomplished by use of (i) data on hand, (ii) data from another Government agency or commercial source, (iii) an on-site inspection of plant and facilities to be used for performance on the proposed contract or (iv) any combination of the above. Pre-award surveys shall be conducted in accordance with Appendix K, Pre-Award Survey Procedures.

(b) *Circumstances Under Which Performed.* A pre-award survey shall be required when the information available to the purchasing office is not sufficient to enable the contracting officer to make a determination regarding the responsibility of a prospective contractor (but see (c) below). The contracting officer shall request a pre-award survey on Pre-Award Survey of Prospective Contractor (DD Form 1524) (see F-200.1524) in the detail commensurate with the dollar value and complexity of the procurement. In requesting a pre-award survey, the contracting officer shall call to the attention of the contract administration office any factors which should receive special emphasis and state whether the purchasing office will participate in the survey (see Appendix K-203.1(b). The factors selected by the contracting officer shall be applicable to all firms responding to the solicitation and shall be considered in all pre-award surveys performed for the same solicitation. In the absence of specific instructions from the purchasing office, the scope of the pre-award survey shall be determined by the contract administration office and a normal time frame of seven working days after receipt of request shall be allowed for conducting the survey and submitting the report, recognizing that in unusual circumstances exception from the normal time frame may be requested.

HAZARDOUS ITEM CONTRACT SAFETY SURVEY REPORT

CONTRACTOR:

ADDRESS:

TELEPHONE:

CONTRACTOR SAFETY DIRECTOR:

TELEPHONE:

ITEM INVOLVED:

IFB/RFP/RFQ/CONTRACT NO:

PREPARED BY: DATE:

INCLOSURES: A-X (See Table of Contents)

NOTE: Depending upon the material, pyrotechnic or ammunition involved, each Safety Survey will vary to some extent. The safety items listed in A through X are examples of equipment, conditions, construction, design features, etc., which may be applicable to ensure safe production of the product. The Survey Report should be prepared in narrative form with comments pertaining to the type of equipment, conditions, etc., and whether they are adequate or inadequate. Scaled maps of plants should indicate the buildings where the item or material will be produced and present a spot check of compliance with explosive quantity distance requirements.

DRDAR-SF Form 407 Mar 78 Replaces SARPA Form 1493 Aug 73 Which is Obsolete

TABLE OF CONTENTS

<u>NOTES</u>: 1. Numbers appearing after a subject:

a. In the clear, they refer to paragraphs in the DOD Safety Manual 4145.26M.

b. In ( ), they refer to paragraphs in the DARCOM Safety Manual DARCOMR 385-100 unless otherwise noted. The requirements of these DARCOM standards will have been included in the IFB/RFP/RFQ/Contract in the Safety Information, Part 9, of Major Component Safety Data Statement, when specific requirements are necessary beyond that indicated in the DOD Safety Manual.

2. A desk audit is acceptable; however, it must be based on a previous Pre-award Survey which was conducted within the last six months. A copy of the detailed Hazardous Item Contract Safety Survey Report upon which the desk audit is based must be forwarded.

MAJOR COMPONENT SAFETY DATA STATEMENT (ARMCOM Suppl 1 to AMCR 385-17)	DATE
MATERIAL/COMPONENT/ASSEMBLY	NUMBER REVISION
APPLICABLE ASPR SAFETY CLAUSE	

SENSITIVITY

PA FRICTION TEST/FIBER SHOE	PA FRICTION TEST/STEEL SHOE
IMPACT TEST (For comparison – Lead Azide 3''; TNT 14''; RDX 8'')	BUREAU OF MINES TEST ELECTROSTATIC DISCHARGE (For comparison – Lead Azide 0.0070 joules; ignitor comp 0.21 joules; black powder >12.5 joules)

HAZARDS

FIRE	FLASH POINT SOLVENTS
AUTO IGNITION TEMPERATURE	PARTICLE SIZE
COMBUSTION PRODUCTS	

FLAMMABLE LIMITS	VAPOR-AIR MIX	LOWER PERCENT	UPPER PERCENT	
EXPLOSION				
EXPLOSIVE LIMITS	VAPOR-AIR MIX	LOWER PERCENT	UPPER PERCENT	DUSTS
EXPLOSIVE TEMP (5 Sec)	TOXIC			

IN-PROCESS HAZARD CLASSIFICATION

SPECIAL REQUIREMENTS (Continue on reverse if necessary)

SHIPPING/STORAGE CLASSIFICATION OF ITEM WHEN PACKAGED IN ACCORDANCE WITH APPROVED PACKING DRAWINGS

AMC HAZARD CLASS	AMC COMPATIBILITY GROUP
DOT BILL OF LADING CLASS	DOT CONTAINER MARKING
PREPARED BY	SEGMENT
CONCURRED	SAFETY OFFICE

ARMCOM Form 47-R, 1 JUN 74 Page 7, Fig 1 Slide #4

A. LICENSES FOR HANDLING EXPLOSIVES: Obtain a copy of license or permit authorizing plant to handle materials. State and/or local.

Slide #5

B. <u>Organization</u>: Obtain an organization chart. If none available, make one up for the area under consideration.

Slide #6

C. <u>SAFETY ORGANIZATION</u>: Titles, duties and training.

SAFETY PROGRAM

a. Total plant safety rules.

b. Implementation plan with responsibilities.

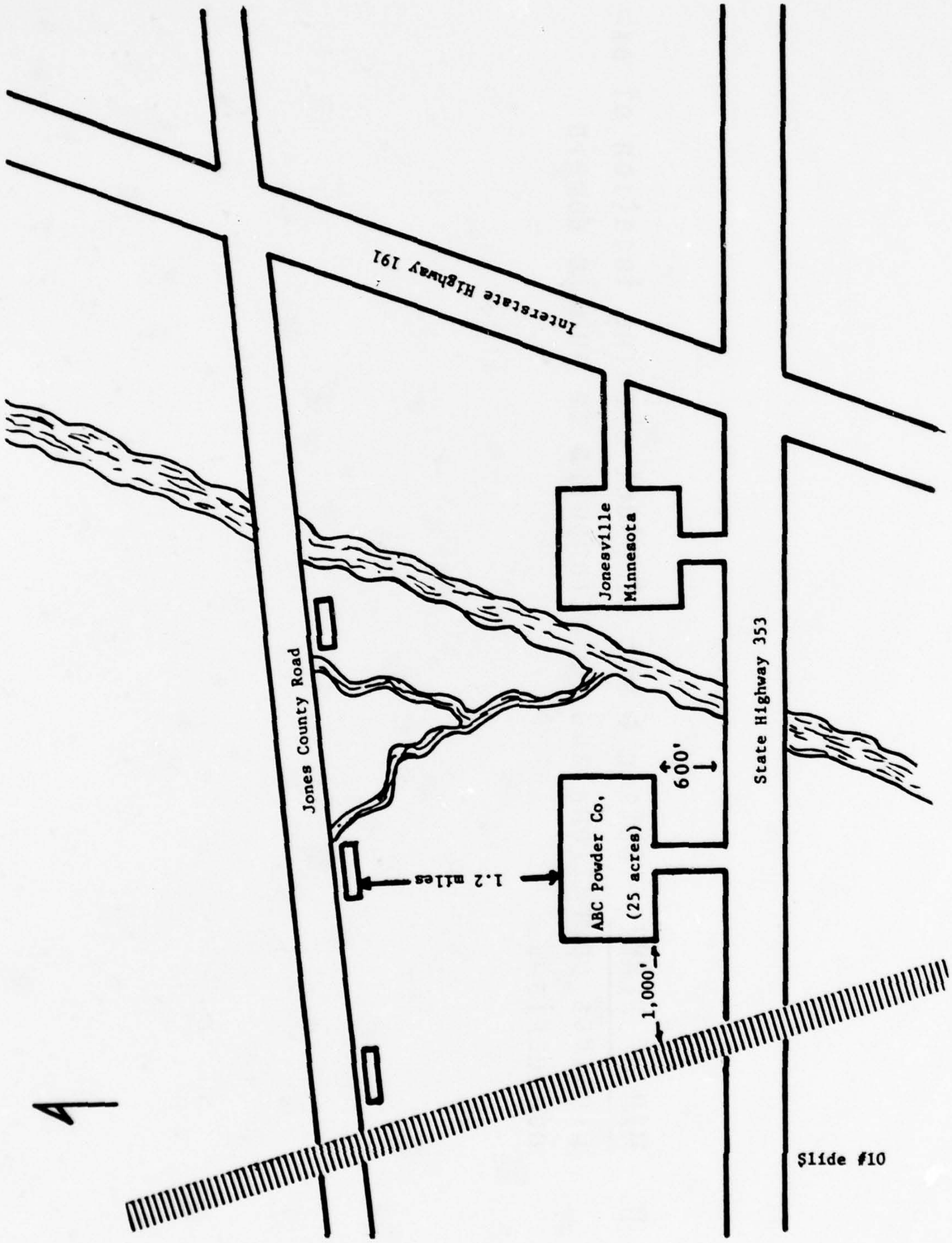
c. Training program to include:

   (1) New hires

   (2) New production

   (3) Continuing instruction

D. MAP OF PLANT: Obtain a map of plant showing location of explosives operations and relationships to public domain boundaries.



Interstate Highway 191
Jonesville
Minnesota
Jones County Road
State Highway 353
600'
ABC Powder Co.
(25 acres)
1.2 miles
1,000'

Slide #10

E. PRIME AND/OR SUBCONTRACTORS INVOLVED: A list of other plants involved with this contractor for the parts of this contract which involve hazardous materials.

F. <u>CONTRACTS:</u> Other hazardous contracts contractor is currently working on. Past experience.

THE ABC POWDER COMPANY
Jonesville, Minnesota

ACTIVE CONTRACT LIST

	Contract Number	Customer	Effective Date	Item	Completion Date	Production
1.	DAAA21-78-C-0000	Picatinny	3-8-78	MK46 Flares	7-2-78	Bldg. A-3 A-4 A-5
2.	DAAH01-78-C-0000	Redstone	4-15-78	Squibs	8-15-78	Bldg. A-2
3.	DAAA21-77-C-0000	Picatinny	10-1-78	W112 Tracking Flares	10-1-79	A-3 A-4 Ignition Unit from Harrison Plant
4.	N00174-78-C-0000	NWSC/Crane	11-15-78	R&D Missiles	12-15-79	A-7 Propellant subcontracted to QED Propellant Company, Smithville, Oregon

Slide #13

J. <u>STATIC ELECTRICITY:</u> 502

-record of grounding tests 502c
-conductive floor tests 502d

K. <u>LIGHTNING PROTECTION</u>: 504 (Chapter 8)

-tests 504
-emergency procedures during electrical storms 503

P. <u>FIRE PROTECTION:</u>

-fire plans 605

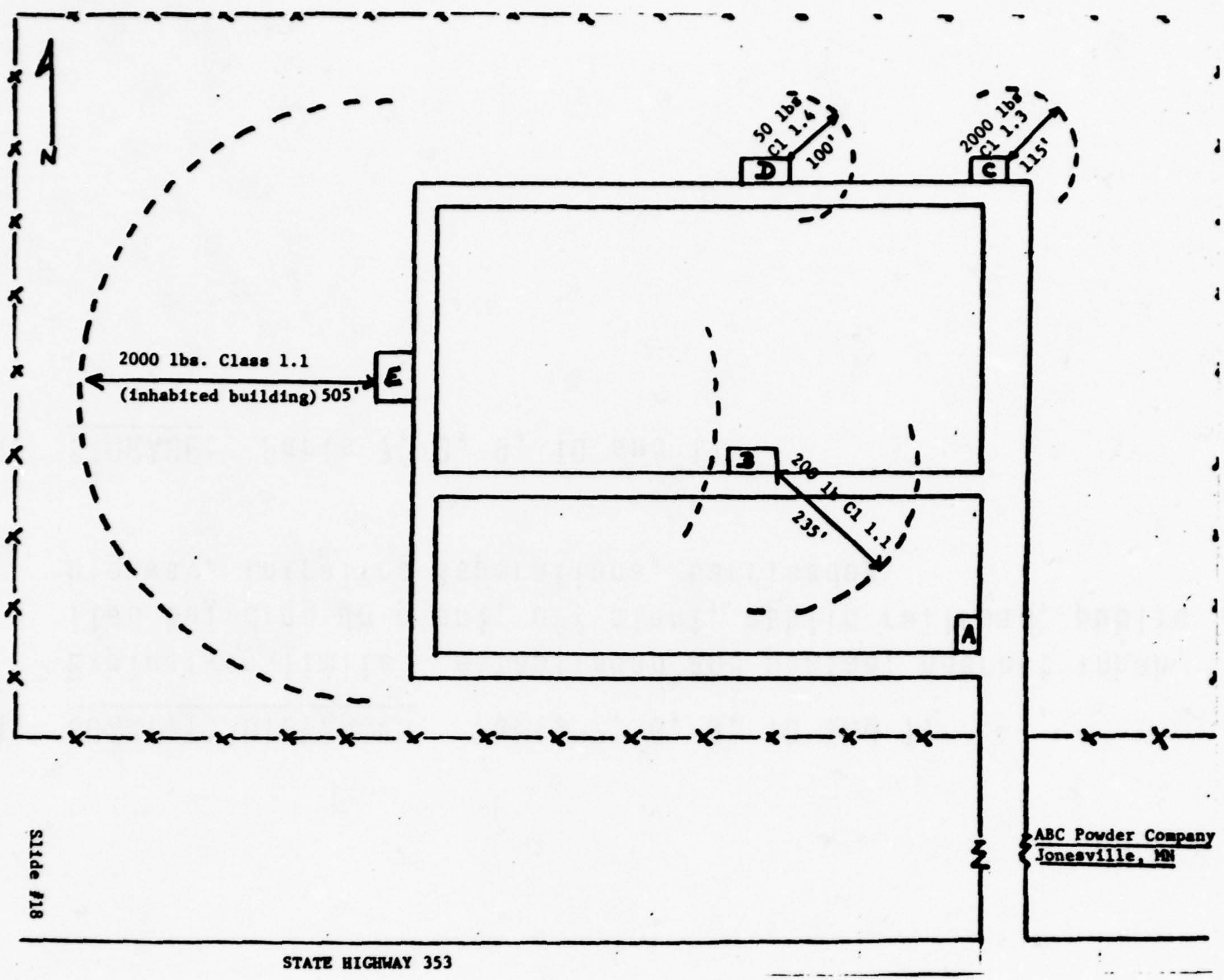
-fire fighting organization (plant, municipal)

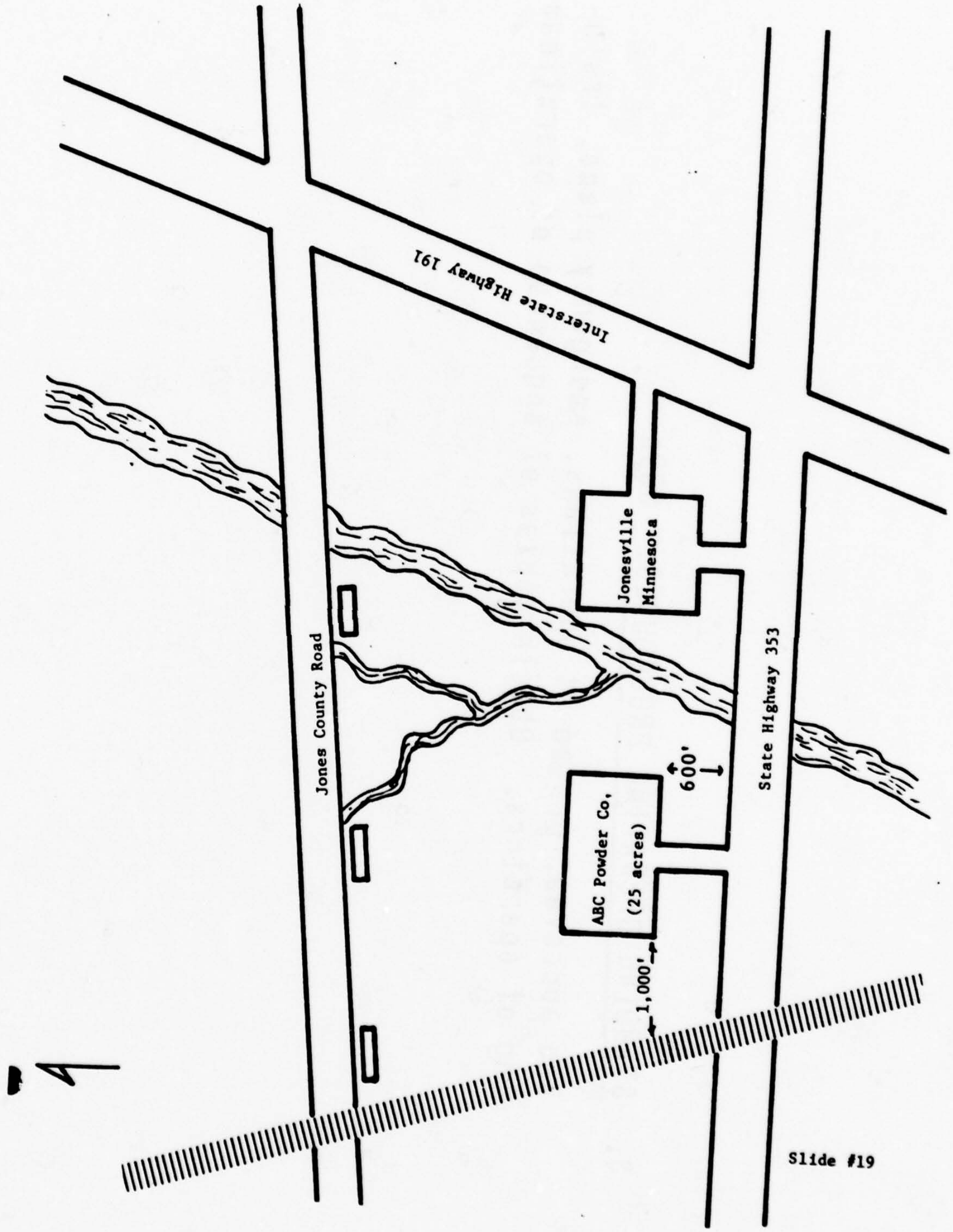
-copy of mutual assistance agreement with municipal forces

Q. <u>QUANTITY DISTANCES</u>: Parts 7, 8, 9, 10 and 11

Explosives limits - established and posted; nearest inhabited building on plant, off plant, public railroad, public highway, intraline separations, barricades.

R. <u>STORAGE</u>: Parts 7, 8, 9, 10 and 11


N
50 lbs
Cl 1.4
100'
2000 lbs
Cl 1.3
115'
2000 lbs. Class 1.1
(inhabited building) 505'
E
D
C
A
200 lb Cl 1.1
235'
ABC Powder Company
Jonesville, MN
Slide #18
STATE HIGHWAY 353


Interstate Highway 191
Jonesville
Minnesota
Jones County Road
State Highway 353
600'
ABC Powder Co.
(25 acres)
1,000'

Slide #19

S. STANDING OPERATING PROCEDURES: 603a

Who approves, posted at operations, emergency plans, training of operators. Obtain copies of sequences of operations.

ABC POWDER COMPANY

STANDARD OPERATING PROCEDURE:

W112B FLARE, INFRARED TRACKING

PAGE 4

ISSUE 1

DATE 8-25-78

BLDG. 101

LOCATION Ignition Mix 90/10

EXPLOSIVE LIMIT 50 pounds

PERSONNEL LIMIT 2 operators, no transients

JOB DESCRIPTION

1. Place barium chromate in Simpson mixer.
2. Add alcohol to mixer.
3. Retire to control room and activate mixer.
4. When thoroughly mixed, stop mixer and add boron.
5. Return to control room and activate mixer.
6. When thoroughly mixed, remotely dump into drying pans & remove to holding bay for delivery to the cure house.

SAFETY AND QUALITY NOTES

SAFETY

1. All equipment & tables will be grounded & mechanically checked daily.
2. Mixer cubicle will be interlocked to deny entry while mixer is in operation.
3. Road to the blender building will be barricaded.
4. Clothing requirements:
   cotton undergarments
   conductive footwear
   flame retardant coveralls

   In addition, when handling exposed, completed mix, aluminized gloves & hood w/face piece are required.

SOP APPROVAL

QUALITY ACD DATE 8/4/78

SAFETY ZSE DATE 8/5/78

MFG JK DATE 8/5/78

PROJ. MGR. SK DATE 8/6/78

Slide #21

T. <u>TRANSPORTATION</u>: Part 13

Inspection stations (motor vehicle and railroad), driver qualifications, rail facilities, instructions to drivers, aircraft, water transportation, materials handling equipment (MHE), training of MHE operators.

U. <u>OPERATIONS</u>:

-layout of operations, obtain drawing 603a(1)

V. TESTING: Part 4

Layout, SOP, misfire procedures, who is in charge, personnel shelters, and observation points, training, copy of FAA airspace clearance (AR 95-50).

Slide #24

W. COLLECTION AND DISPOSAL: Part 15

Decontamination procedures, waste collection, collection systems, cleaning, destruction site, burning procedures, layout of burning and detonation areas, training of operators.

Slide #25

X. <u>SPECIAL SURVEY REQUIREMENTS:</u>

Refer to Major Component Safety Data Statements for this IFB/RFP/RFQ/Contract for unique conditions which may require special attention.

Slide #26

MAJOR COMPONENT SAFETY DATA STATEMENT

(ARMCOM Suppl 1 to AMCR 385-17)

MATERIAL/COMPONENT/ASSEMBLY	DATE
	NUMBER
	REVISION
APPLICABLE ASPR SAFETY CLAUSE	

SENSITIVITY

PA FRICTION TEST/FIBER SHOE	PA FRICTION TEST/STEEL SHOE
IMPACT TEST (For comparison – Lead Azide 3'', TNT 14'', RDX 8'')	BUREAU OF MINES TEST ELECTROSTATIC DISCHARGE (For comparison – Lead Azide 0.0070 joules, igniter comp 0.21 joules, black powder >12.5 joules)

HAZARDS

FIRE	FLASH POINT SOLVENTS
AUTO IGNITION TEMPERATURE	PARTICLE SIZE
COMBUSTION PRODUCTS	

FLAMMABLE LIMITS	VAPOR–AIR MIX	LOWER PERCENT	UPPER PERCENT	
EXPLOSION				
EXPLOSIVE LIMITS	VAPOR–AIR MIX	LOWER PERCENT	UPPER PERCENT	DUSTS
EXPLOSIVE TEMP (5 Sec)	TOXIC			

IN-PROCESS HAZARD CLASSIFICATION

SPECIAL REQUIREMENTS (Continue on reverse if necessary)

SHIPPING/STORAGE CLASSIFICATION OF ITEM WHEN PACKAGED IN ACCORDANCE WITH APPROVED PACKING DRAWINGS

AMC HAZARD CLASS	AMC COMPATIBILITY GROUP
DOT BILL OF LADING CLASS	DOT CONTAINER MARKING
PREPARED BY	SEGMENT
CONCURRED	SAFETY OFFICE

ARMCOM Form 47-R, 1 JUN 74 Page 7, Fig 1

TOPIC: Legal Aspects of Contract Safety, Contractor Corrective Actions and Mishap Reporting

PRESENTER: Pete Zakrzewski - DCASR St. Louis

Good morning, ladies/gentlemen. I will present various legal aspects of contract safety, Contractor corrective actions and mishap reporting. This information should be of interest if you are either a current Department of Defense (DoD) Contractor or contemplating doing business with the DoD.

DoD policy requires that the safety requirements of DoD 4145.26M, titled, "DoD Contractors' Safety Manual for Ammunition, Explosives, and Related Dangerous Material", be applied to all contracts involving ammunition or explosives (A&E).
This is the DoD 4145.26M manual. To accomplish this policy, all solicitations and resulting contracts involving the development, testing, storage, manufacture, modification, renovation, demilitarization, packaging, transportation, handling, disposal, inspection, repair or other use of ammunition or explosives will include the clause set forth in Defense Acquisition Regulation (DAR) 7-104.79. The DoD makes a sincere effort to administer contracts containing this clause in such a manner as to assure safety without unnecessary application of the requirements of the DoD 4145.26M Safety Manual to Contractor operations or facilities not directly involved.

We will now review the DAR 7-104.79 safety clause (view-graphs of clause). This clause is titled, "Safety Precautions for Ammunition and Explosives."

The first part of Paragraph a essentially reiterates the DoD policy to insert this clause in all contracts which may involve the development, testing, etc., or any other use of ammunition or explosives. Note that the terms "ammunition" and "explosives" exclude inert components containing no explosives, active chemicals or pyrotechnics.

Subparagraph a epitomizes important definitions. As used in this clause:

(i) "ammunition" and "explosives" have the meaning set forth in the DoD 4145.26M Safety Manual;

(ii) "accident" means an event causing damage or injury involving ammunition or explosives which results in one or more of the following:

(1) one or more fatalities, *

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(2) one or more disabling injuries, *

(3) ten or more nondisabling injuries, *

(4) damage to Government property exceeding $10,000,

(5) production interruption exceeding 24 hours. The asterisks after numbers (1), (2) and (3) refer to meanings as defined in American National Standard Institute Z16.1, titled, "USA Standard Method of Recording and Measuring Work Injury Experience." A disabling injury is sometimes referred to as lost-time injury and includes calendar days subsequent to the day of the mishap in which an employee is unable to perform effectively throughout a full shift, the essential functions of a regularly established job. There are many instances where an accident involving an employee does not result in death, loss of both eyes or a finger, but which does result in one or more days away from work.

Subparagraph b relates that the DoD Contractor must comply with the DoD 4145.26M Safety Manual and any other additional or more stringent requirements included in the contract. Contracting Officers refrain from referencing ammunition or explosives safety publications of the DoD component (e.g., Army, Navy, Air Force) in their entirety, as required, in contracts issued to Contractor-owned - Contractor-operated facilities. However, they may select and identify in the contract applicable paragraphs or portions of such publications.

This subparagraph also references Contractor corrective action in case of any noncompliance with the Safety Manual. If a Contractor is notified by the Contracting Officer of such a noncompliance, he is expected to take corrective action immediately within the time specified. Normally, Contractor corrective action is requested within 30 days, or on a mutually agreeable schedule indicating the completion date when an unusual circumstance exists. If the Contractor fails or refuses to correct a noncompliance in the specified timeframe, the Contracting Officer may direct the Contractor to cease performance on all or part of this contract, or until satisfactory corrective action has been taken. In addition, he may at any time remove Government personnel from the hazardous area. However, should these actions be implemented by the Government and it be determined that the Contractor had, in fact, complied with the Safety Manual, the Contractor will be entitled to equitable adjustments in the contract.

Subparagraph c requires the Contractor to notify the Contracting Officer after an accident involving ammunition or explosives. It should be emphasized that the definition of an

accident was described previously in this clause. The Contractor will also, in accordance with the contract or as required by the Contracting Officer, conduct an investigation and submit a written report of the accident to the Contracting Officer.

Subparagraph d, in essence, notes that the Contractor cannot rely on the requirements of this clause or on any Government surveillance or enforcement thereof, or lack thereof, etc., in discharging the Contractor's responsibility for the safety of his personnel, property and the general public in connection with the performance of the contract. Also, this will not impose or add to any liability of the Government for such safety.

Subparagraph e notes that the Contractor, prime or subcontractor, must insert the substance of this clause, including this paragraph (e) in every subcontract which involves ammunition and explosives. This is important. There are numerous examples throughout the DoD Contractor community where abnormalities have been uncovered.

Subparagraph f indicates that the Contractor is not relieved from complying with applicable federal, state and local laws, etc., in connection with the ammunition and explosives contract.

Paragraph b outlines special requirements the Contractor must implement when the contract involves ammunition and explosives shipments by military aircraft or to an aerial port of embarkation.

This concludes my presentation - Thank you.

SPECIALIZED SAFETY CERTIFICATION PROGRAM

John Scheer - Safety Manager - DCASR Chicago

My topic is the Specialized Safety Certification Program. In order to understand the need for such a program, let us begin with an orientation to some of the main functions of Specialized Safety within the Defense Contract Administration Services (known as "DCAS").

DCAS is a major arm of the Defense Logistics Agency (DLA) and provides contract administration services in support of the Military departments, other DoD components, NASA, and any other Government agency or element who desires our services. In addition, DCAS handles foreign contracts, channeled through the State Department, and provides requested services.

The Specialized Safety Program is a portion of the functions performed within DCAS. Why the word "Specialized"? Because the prime function for which this program was developed is to oversee the safe production of explosives and explosive devices primarily in privately owned and operated factories -- our private sector ammunition and explosives production base. The bulk of the remaining workload involves specific risks in processes or products other than explosives being supplied to the Government by private sector firms. Highly volatile products, aircraft ground safety, critical government property, LASERs, radiation safety -- these are some of the areas of specific risk. At times, our work can take us to the frontiers of existing knowledge as some of the firms hold Research and Development contracts in explosives and other high risk areas.

Field safety personnel participate in preaward surveys as members of the preaward survey team whenever requested by the Procuring Contracting Officer (PCO) or the Preaward Monitor, or when it is determined by the DCASR Chief of Specialized Safety or higher authority to be necessary. During the preaward phase, a determination is made as to the prospective contractor's ability to produce safely and his ability or inability to perform within the guidelines of any specific safety clauses imposed by the contract.

Postaward surveys continue through the life of selected contracts. A priority number for surveillance is assigned each contractor based on the degree of risk involved in fulfilling the contract and the presence or absence of any specific, mandatory safety clauses. Those firms engaged in explosives work are surveyed on a quarterly basis and are included in Priority 1 as are flight facilities, though these latter are surveyed semiannually. Last, but not least, in this Priority 1 category are "Into-Plane Fuel Contractors" -- those firms which service Government aircraft at private and commercial airports around the nation. These are surveyed annually. Priority 2 facilities are those which are Government-Owned Contractor-Operated (GOCO), those with specific safety clauses in their contracts but who are not working with explosives, and those with specific risks -- a category which we discussed a few moments ago. These facilities are surveyed annually. The final category, Priority 3, includes all other private contractors. These are normally not surveyed except as requested or when determined necessary by the DCASR Chief of Specialized Safety or higher authority; in other words, they are surveyed on a "Management-by-exception" basis.

Determination of most Priority 1 contractors is usually fairly simple since mandatory safety clauses covering explosives operations, refueling standards, or flight test functions are normally included in the contract and the PCO requests a Preaward Safety survey. But, when Priority 2 Specific Risks are involved, it is the Government's Quality Assurance Representative -- the QAR who works at the plant -- that Specialized Safety must rely on. By regulation, the QAR is required to submit to Specialized Safety on an annual basis a list of his contractors working with hazardous materials or performing dangerous operations. A determination is then made as to the most hazardous situations, and a schedule for surveying these contractors is established. Government Property Administrators within DCAS are also contacted by Specialized Safety to determine which firms possess critical Government property.

Safety surveys conducted at contractor facilities generally uncover deficiencies, and these deficiencies can be tied to contractual requirements which the contractor has agreed to comply with. This includes providing a safe working environment for the QAR.

During the survey, the Safety Specialist determines if the contractor's safety program is satisfactory or not. If specific risks are not well controlled and safety precautions are inadequate, the contractor is advised to correct the deficient conditions. Normally, the QAR will accompany the Safety Specialist. This alerts the QAR to potential hazards in his plant and enables him to perform more meaningful follow-up on any corrective actions or to alert the Specialized Safety office to suspected safety deficiencies that he may observe. A Specialized Safety follow-up survey may also be required in certain serious circumstances.

Also not to be overlooked is the consultative aspect of our work. Any firm holding an active, DCAS-administered contract can call upon his local Specialized Safety office and receive assistance in improving his safety program. Also, during the course of a regularly scheduled survey, this type of assistance is automatically provided thereby assuring that our Defense production base contractors will be ready and able to provide our Armed Forces with their materiel needs in the event of a national emergency.

Now we all recognize that, try as we might, accidents still will happen on occasion. Of course, it is the contractor's obligation, normally, to investigate these and implement corrective actions. However, the assistance of Specialized Safety may be requested.

So much for a brief orientation to the work of Specialized Safety. Now let us talk about the people who staff the program.

It should be fairly obvious from the description of the scope and variety of work involved in Specialized Safety that highly skilled personnel are a must. Otherwise, such an ambitious program would fall apart. So, in order to insure that the personnel staffing this program have the necessary skills, a certification plan combining formal classroom training and on-the-job training (OJT) is utilized.

This program has evolved through several stages over the years. About ten years ago, in 1968, there was no program for training newcomers to the Specialized Safety field within DCAS. And I suppose that it is rather appropriate that I am the person addressing you on the training phase today, because I wrote the very first training program for Specialized Safety during the winter of 1968-1969. At the time, I was on a cross-training detail from my job as an assistant to a QAR in a local factory. I drew on the knowledge of those who were then assigned to the Specialized Safety office, modeled the training program after those for other fields; and, when it was completed, the Chief of Specialized Safety submitted it to DLA and then to the Civil Service Commission. After it was approved and printed as an official document, I took a downgrade to a trainee level and became the first formal Specialized Safety Intern.

From that rather rough-cut beginning, the training program has developed, over the years, into a finely honed process under the guidance of the safety experts at DLA Headquarters. The program as it now exists provides for certification in two distinct areas -- Explosives Safety and Industrial Safety. Specialized Safety personnel must be certified in both areas to perform the overall required safety mission and functions. However, as a specialist becomes certified in one or the other area, he or she may be assigned to accomplish on-site, independent surveys pertaining to that safety certification area only.

Any one of three methods of qualifying for explosives or industrial safety certification may be used by trainees. These methods were devised with the point of view that personnel being brought into the Specialized Safety Program at any of the field Regional offices will have varying degrees of past on-the-job experience and/or safety training.

The first method of certification requires that the nominee must have received all prescribed training, have had at least one (1) year of safety experience in the desired area of certification, and have a current satisfactory performance appraisal. Admittedly, these types of people are difficult to find, but there are several schools under the Army Field Safety Program which produce such personnel. Also, it is possible to gain course equivalency, but final determination of this rests with Specialized Safety Headquarters at DQMSO in Atlanta.

The second method requires that the nominee must have received at least 50% of the prescribed training courses in the desired area and has at least three (3) years' safety experience, 75% of which would be in the desired certification area within the past six (6) years and has a current satisfactory performance appraisal. This method is less strict and recognizes that career safety personnel are available and may meet the experience criteria stated above. Again, some equivalency credit may be authorized.

The third method of gaining certification requires the nominee to have received at least 50% of the prescribed training courses for explosives safety certification and to have conducted at least three satisfactory safety surveys at <u>each</u> explosives facility for which he will be responsible. For the surveys to be considered satisfactory, a certified safety specialist

will have to have been with the nominee and have considered his performance to be satisfactory. For industrial safety certification, the nominee must have received at least 50% of the prescribed training courses and have had at least one (1) year of hands-on safety experience at appropriate contractor facilities in the company of a certified Safety Specialist/Manager who judged his performance to be satisfactory. There must, again, be a current satisfactory performance appraisal on the nominee.

Refresher training is also a part of the program. In order to remain certified, an individual must attend at least one listed explosives safety course or the DDESB Seminar every three years.

The formal schooling portion of the training program includes two courses which cover both explosives and industrial safety, four courses which are purely explosives safety, and eight more covering various aspects of general industrial safety. The course list may be found in DLA Handbook 8220.1, pages 54 through 61, line items K01 through K14.

I have given you a brief overview of the main functions of Specialized Safety in DCAS. The certification program which we have just discussed assures that our personnel have had the training and experience to qualify them to perform the extremely responsible and, oftentimes, critical operations of Specialized Safety.

Thank you for your attention.

THE HISTORY OF THE QUANTITY DISTANCE TABLES FOR EXPLOSIVE SAFETY

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This work was supported in part by the Safe Transport of Munitions (STROM) Program of the Military Traffic Management Command.

NOTE: English units are used throughout this paper to make comparison to older data easier and place less burden on the readers.

I. INTRODUCTION

The Ballistic Research Laboratory (BRL) is investigating the mechanisms for initiation of detonation of stored munitions. The goal of this effort is to reduce the vulnerability of stored munitions, and prevent or reduce the probability of propagation of explosion between adjacent munitions stores. Application of the techniques developed will range from small quantities, such as might be found in armored vehicles to larger quantities encountered in, shipment, or in storage depots. As part of this program an investigation has been made of the source and development of quantity-distance regulations as defined in AMCR-385-100[1] and TM 9-1300-206[2]. It is the results of this investigation which will be reported here.

II. QUANTITY-DISTANCE TABLES

There are a number of different quantity-distance tables, the application of which depend on the nature of the potential threat and the degree of protection required. Different nations have differing standards to be met, but there is a trend toward agreement on standards. This is exemplified by the recent adoption (1977) of the United Nations classification system by the United States, United Kingdom and many NATO countries. For the US Army, ammunition and explosives are classified on the basis of their reactions to specified initiating influences as described in TB 700-2[3].

The classification system recommended for international use by the United Nations consists of nine classes for dangerous goods with ammunition and explosives included in UN class 1, explosives. Class 1 explosives are subdivided into four parts as follows. Class 1.1 represents explosives and ammunition which when stored or shipped with only small separation distance between items, and may detonate "en masse". Class 1.2 is for fragment producing cased explosives, such as projectiles. This class is further subdivided into four subclasses dependent on the range of the fragment threat in feet, i.e., 400, 800, 1200, or 1800 feet. This is designated as 1.2 (04), 1.2 (08), 1.2 (12) or 1.2 (18). Class 1.3 is for materials which represent a severe fire threat. Class 1.4 is for materials which represent a moderate fire threat. Table I shows the UN hazard classes with the appropriate conversion from the superceded US classification system. This table was extracted from AMCR 385-100[1] Change 3, dtd 4 October 1977, Chapter 19.

Table I. Conversion From Superseded US Hazard Classification System to UNO System

Superceded Class	UNO Class	Hazard
7	1.1	Mass detonation with possible fragment threat
6	1.2 (18)	Non mass detonating with most fragments falling within the distance indicated
5	1.2 (12)	
4	1.2 (08)	
3	1.2 (04)	
2	1.3	Mass fire
1	1.4	Moderate fire

The common quantity-distance tables are listed below with their definitions as they are given in AMCR 385-100[1], Chapter 17.

- Inhabited Building Distance. This distance is the minimum permissible distance allowed between a quantity of explosives and any building inhabited by the public or where people are accustomed to assemble, both within and outside government establishments. Land outside the boundaries of government installations is included as a possible site for inhabited buildings. This minimum distance provides a high degree of protection against structural damage based on blast or shock wave effects to frame or masonry buildings. It does not provide protection against glass breakage. Personnel injury from flying glass fragments is a possibility.

- Public Traffic Route Distance. This distance is the minimum permissible distance between an explosives site and public highways or

railroad lines. It is 60% of the inhabited building distance. The lesser distance is based on the greater resistance of rail and road vehicles to blast effects. It is additionally reasoned that safety is not compromised because these items are only exposed for limited periods as they pass by the explosive site.

• Intraline Distance. This is the minimum permissible distance between two buildings within one operating explosive/ammunition production line. The purpose of the intraline distance is to prevent the propagation of explosions by blast effects between buildings. Separation of service magazines is an example. Distances are based on the larger quantity of explosives involved in either building.

• Magazine Distance. This is the minimum permissible distance between storage magazines, and is based on the type of magazine and the quantity of explosive involved. It is designed to prevent propagation of explosives by blast, and provides reasonable protection against propagation by fragment impact. It does not preclude severe structural damage to magazines adjacent to a magazine suffering an accidental explosion.

• Fragment Distance. This distance applies to specific explosive items which generate hazardous fragments, such as fragmenting projectiles and heavily cased explosives. For the specified distance the fragment distribution and energy is, less than one fragment of energy 58 ft-lbs per 600 square feet, (78 Joules per 56 m^2). This distance applies to class 1.2 items with distances as previously described of 400, 800, 1200 and 1800 feet. This distance also is the inhabited building distance for class 1.2 items and is designated to protect individuals in the open from fragment threats.

Excluding the fragment distance, which is specific for each munition, the remaining distances each correspond to a specific scale distance $Z = R/W^{1/3}$, where R is the distance in feet from the explosive and W is the weight of the explosive in pounds. The scale distance can be related to a specific value of overpressure. Table II gives the 1977 scaled distances for each of the above defined quantity distances used by the United States, and the approximate value of the side-on-pressure associated with each scale distance.

Table II. Scale Distance and Side-On-Pressure For Specified Quantity-Distance Categories

Quantity Distance	Scale Distance	Side-On-Pressure p.s.i.
Inhabited Building		
1 to 100,000 lbs	40	~ 1.1
100,000 to 250,000 lbs	40→50	
250,000 to 1,500,000 lbs	50	~ 0.93
Public Traffic Route		
1 to 100,000 lbs	24	~ 1.8
100,000 to 250,000 lbs	24→30	
250,000 to 1,500,000 lbs	30	~ 1.4
Intraline	18	~ 2.5
Magazine Distance (dependent of type of magazine)	1.1→11	~ 700 → 5.3

III. HISTORICAL BACKGROUND[4,5]

The Inhabited Building Distance Tables, or "The American Table of Distances" as it was called earlier, had its genesis in 1909. In that year Col. B. W. Dunn, Chief Inspector of the Bureau of Explosives, representing the American Railroad Association, brought to the attention of the manufacturers of explosives in the United States a potentially hazardous situation. He demonstrated the need for some radical changes in the location of explosive magazines with respect to railway lines. As a result of Col. Dunn's efforts the Association of Manufacturers of Powder and High Explosives appointed a committee to study the problem. Foreign regulations were examined, but were not found to be suitable, and an extensive investigation of explosive accidents world-wide was undertaken. The principle data compiled were the quantity of explosive involved in an accident, and the distance to which damage extended. The committee assembled descriptions of the accidents, and tried to assess the extent of the damage for 122 explosive accidents between the years 1864 and 1914. These descriptions along with eighteen additional explosive accidents are included in Assheton's[4] work.

As a result of this study the American Tables of Distances was published which gave the minimum permissible distance allowed for inhabited buildings for quantities of explosive up to 1,000,000 pounds. Assheton noted that the table could be approximated quite well by a curve which related the distance to a constant times the cube root of the explosive weight, but this was not exploited until much later.

In compiling the data on the accidental explosions it was always noted, as to whether or not, the explosive source was barricated, either naturally or artificially. This led to the interesting assumption, that if the source was barricaded then the safe distance was half that of an unbarricaded source of like weight. There was no explanation or justification given for this assumption, and it later caused much debate within groups charged with explosive safety regulations. Railroad distances were set at 60 percent of the inhabited building distance and public highway distances at half the railroad distance. The highway distance was later changed to the same value as railroad distances. The selection of 60% was rather arbitrary and the reasoning is given in the following quotation from Assheton[4].

> "... after as careful a consideration as possible, it was concluded that reasonably safe distances from railroads were provided by taking 60% of the inhabited building distances, the reasons for the conclusion being:
>
> The lesser height and small area of railroad cars exposed to resist concussion, as compared with buildings.
>
> The fact that while a building is stationary and subject to any risk constantly, the presence of a train is only temporary."

It is interesting to note that the wording in AMCR 385-100[1], Chapter 17, paragraph 3 is very nearly identical to the above quotation.

The American Table of Distances was established in 1915. The state of New Jersey adopted them as state law in 1925 and the United States Government adopted them in 1928 following the Lake Denmark accident[5], which incidently marked the beginning of what now is the Dept. of Defense Explosive Safety Board. The most remarkable aspect of this table was that in spite of the large scatter in the data (see Figure 1), and the reliance that had to be placed on subjective accounts of the accidents, often several years old; these tables are remarkably close to modern accepted values. The tables remained unchanged for many years. In fact they are given exactly as published in a 1942 US Army Ordnance School Text[6] and in a 1960 explosives handling manual[7].

In 1945 Col. C. S. Robinson who was attached to the Army/Navy Explosive Safety Board published a report[8] in which he questioned the accuracy of the inhabited building distance tables. His primary concern was for large quantities of explosives. He believed the distances specified were inadequate. He was also concerned that modern explosives, being more energetic per unit weight, might also make the distances specified too short for safety. His concern was based primarily on damage resulting from accidents involving large quantities of explosives,

and the fact that World War II mobilization resulted in large quantities of munitions being stored in various port areas. Figure 2 shows the American Table of Distances with data points that were the basis of his concern. Adding to Col. Robinson's concern may have been the accidents at Port Chicago and at Hastings the previous year. Both involved large quantities of Torpex, which was known to be more sensitive than TNT and to have a greater air blast effect. Col. Robinson also questioned the efficacy of barricades at the source in reducing safe distances in this report. He is largely responsible for the work that was initiated following World War II to increase the knowledge and understanding of explosions and their effects.

In the period following the end of World War II extensive explosive blast research was undertaken at many government laboratories. Assheton had noted in 1930 that the American Table of Distances could be approximated by a constant times the cube root of the explosive weight. Extensive testing and measurement of blast pressures under carefully controlled conditions validated this concept. Protection from the effects of blast are now related to a specific scaled distance, as indicated in Table II. Assheton's 1930 value for barricaded explosive sites was 35. The 1977 value for inhabited building distance is 40 for quantities of explosive up to 100,000 lbs and 50 for quantities in excess of 250,000 lbs.

The effectiveness of barricades in reducing blast pressures was a topic that received a great deal of attention in the twenty year period following World War II. Col. Robinson had questioned the efficacy of barricades in his 1945 paper[8] and dealt more extensively with the topic in his book[9]. The Armed Services Explosive Safety Board sponsored a large amount of work to produce data addressing the problem. The difficulty encountered in removing barricaded distances from the inhabited building distance tables is illustrated in a presentation to the Armed Services Explosive Safety Board by the Defense Atomic Support Agency in 1966[10]. In addition to the data and conclusions presented, this report includes a transcript of the discussions following each presentation. The reluctance to abandon the concept that barricades at the source can reduce safe distances for inhabited buildings is clearly evident. A second DASA paper[11] published in 1968 gives a very good summary of the available data and a very complete bibliography of pertinent publications. Barricades were proven to be less effective than previously supposed at distances more than 5 to 8 times the barricade height. As a result the barricaded distance values were eliminated from inhabited building distance tables.

In an attempt to better predict and quantify blast damage to specific targets and target elements, generally in a vulnerability analysis context several authors have incorporated impulse loading with pressure loads to predict a specified damage level. In general curves representing a constant level of damage can be obtained in the pressure-impulse plane. Johnson[12] and Baker[13] show several examples, the former for

total targets and the latter for structural elements. In every case the response of the target and failure mode must be specified. Sewell[14] reported a similar technique in 1964 and more recently Schumacker and Cummings[15] have presented a pressure-impulse blast damage model. Falcon Research and Development Co. under contract to the Armed Services Explosive Safety Board developed models of blast response for ten specified targets. The targets were selected as typically those encountered in quantity-distance tables i.e., a house, public buildings, magazines, aircraft, and vehicles. The models were dynamic interaction models and considered both elastic and plastic deformation of the principle structural elements of each target, and specified acceptable damage levels. A computer program was generated to handle the computations. Where possible comparison is made to actual test data. Calculations were made for five charge weights ranging from 1000 lbs to 9,000,000 lbs. The resulting isodamage curves in the pressure-impulse plane are hyperbolic and similar to those of Johnson[12] and Baker[13].

Figure 3 shows a comparison of the predicted response of a split level ranch style home, and an A frame church structure to current inhabited building distance curves. The specified acceptable damage level for the house is the cracking, but not breaking of the rafters (2" x 8" x 17 feet long, 16 inches on center with 1/2" plywood roof). The specified acceptable damage level for the church was the cracking, but not breaking of laminated roof trusses (7.5" x 16" x 39 feet long, 15 feet on center with a roof of 4" x 8" tongue and groove planks). As can be seen from Figure 3 the house data points fall very nearly on the inhabited building distance curve, but the data points for the church indicate inadequate protection for charge weights in excess of 5000 lbs.

Figure 4 is a similar comparison between calculated safe distances (targets are not overturned) for a bus, a pickup truck with camper, and a house trailer all on a highway, and public traffic route distances currently in effect. In this case the bus, which is the more resistant to overturning of these targets, has a safe distance nearly coincident with public traffic route distances, except for very large charge weights. The other two targets are likely to be overturned at the public traffic route distances. This demonstrates how important the target response and failure mode are to calculating safe distances by this technique. Because the target response is so important to the calculation of safe distances, and because of the diversity of targets that must be protected at inhabited building distances and at public traffic route distances it is unlikely that this technique, which requires computer calculations will have any marked effect on the quantity distance tables. Exceptions might well be made however for those situations where large quantities of explosive are stored or where the public is encroaching on territory adjacent to large storage sites. Other possible exceptions might be special construction at inhabited building distances which by its nature may be more vulnerable to blast damage, for example a curtain wall building with large expanses of glass windows.

IV. CURRENT STATUS OF QUANTITY DISTANCE TABLES

The current US Inhabited Building Distances are compared to the 1977 NATO standards[16] in Figure 5. As can be seen the US values are more conservative for quantities less than 1000 lbs, and less conservative for larger quantities. For example at 10,000 lbs NATO standards require 1206 feet compared to 865 feet to meet US standards and for 100,000 lbs the values are 2600 feet NATO vs 1855 feet US. (NOTE: NATO standards are in metric units

$$D = 22.2\ Q^{1/3} \text{ for } > 4500 \text{ kg}$$

$$D = 5.5\ Q^{1/2} \text{ for } < 4500 \text{ kg}$$

where D is in meters and Q is the weight of the explosive in kg).

The NATO standards[16] for inhabited buildings are based on work reported by the United Kingdom[17] in 1959. In this work standards are multiples of a quantity R_b which stands for the radius of B type damage. "B" damage is defined as: Such severe damage as to require demolition. The data were derived from bomb damage by air blast to buildings during World War II. R_b in terms of explosive weight is given by the formula:

$$R_b = \frac{14\ W^{1/3}}{\left[1 + \left(\frac{7000}{W}\right)^2\right]^{1/6}}$$

where R_b is in feet and W is the explosive weight in lbs. Inhabited building distances were then set at $4R_b$. For explosive weights in excess of about 10,000 lbs the inhabited building distance is approximated by $4\ R_b = 56\ W^{1/3}$. The above formula was the NATO standard in 1970[18]. Except for the change in units the 1977 NATO standard is the same above 10,000 lbs of explosive. For lesser quantities the expression now used is shown below in both English and metric units.

$$R = 12\ W^{1/2} \qquad \text{R in feet W in lbs.}$$

$$D = 5.5\ Q^{1/2} \qquad \text{D in meters Q in kilograms.}$$

Intermagazine distances and intraline distances appear to be about comparable between the US and NATO standards, although NATO intraline distances are slightly more conservative. An exact comparison is difficult because of differences in definitions and descriptions of donor and acceptor sites.

V. CONCLUSIONS

In the author's opinion the most likely change to the Quantity Distance Tables will be in the inhabited building distances tables. It seems logical that the US and NATO will likely come to an agreement on a single standard and probably the US tables will go metric at that time. It also appears that the other tables will become standardized between the US and NATO including definitions and descriptions of donor and acceptor sites.

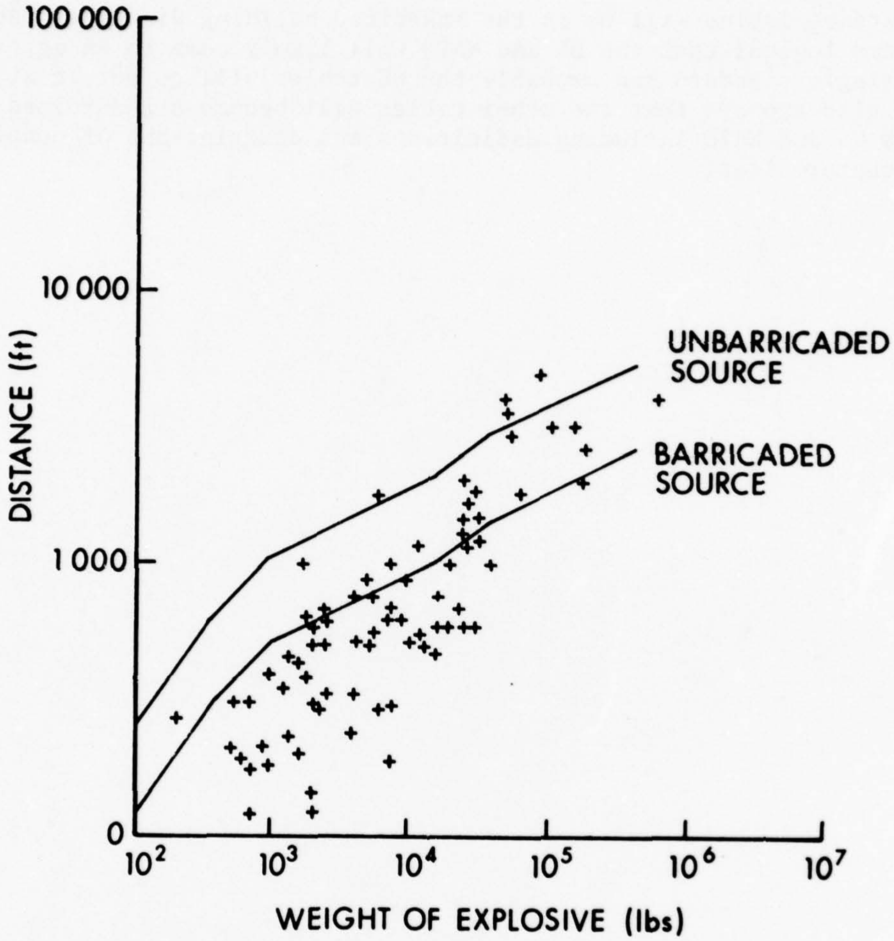

Figure 1. 1915 Inhibited Building Distance Curves with Data Points on Which They Were Based

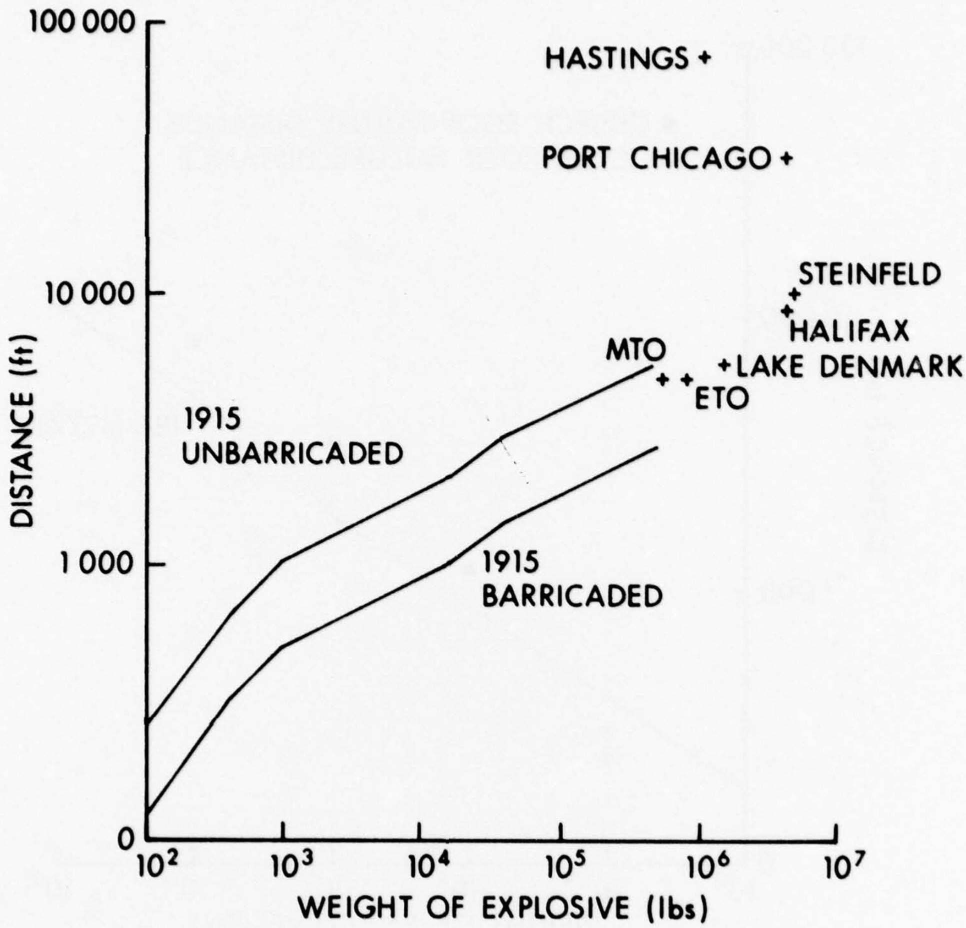

Figure 2. 1915 Inhabited Building Distances with Data Points for Some Large Accidents

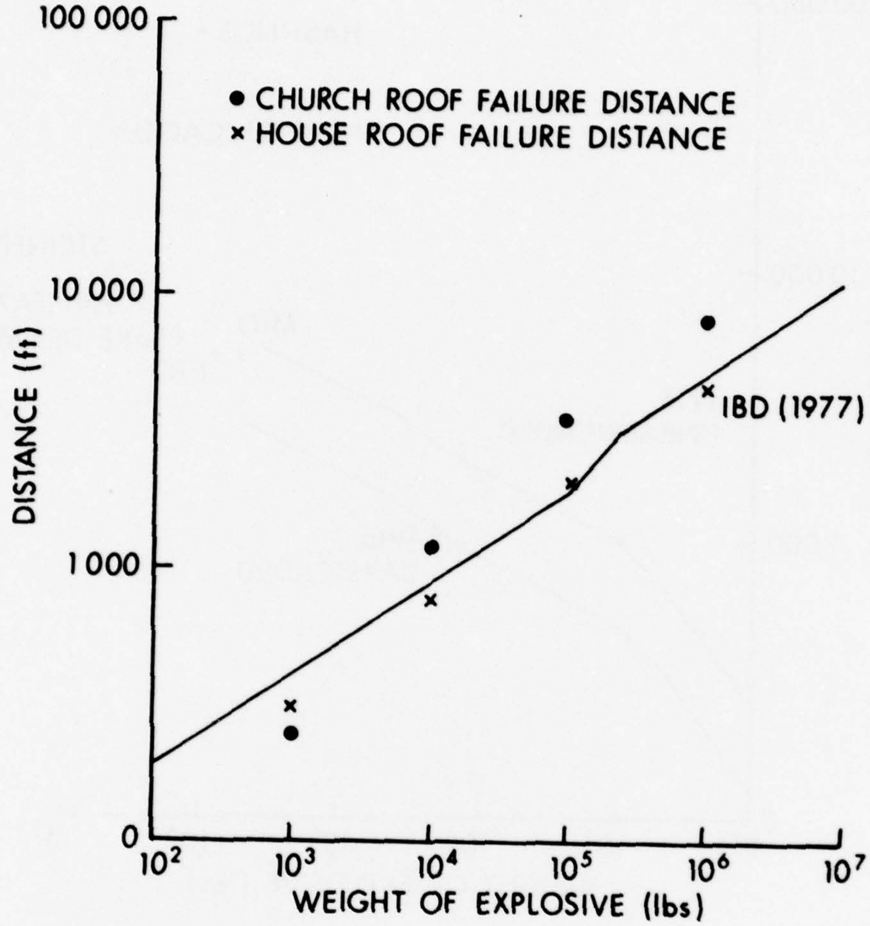

Figure 3. Comparison of 1977 Inhabited Building Distance to Structural Failure Distances Calculated by Falcon Pressure-Impulse Loading Technique

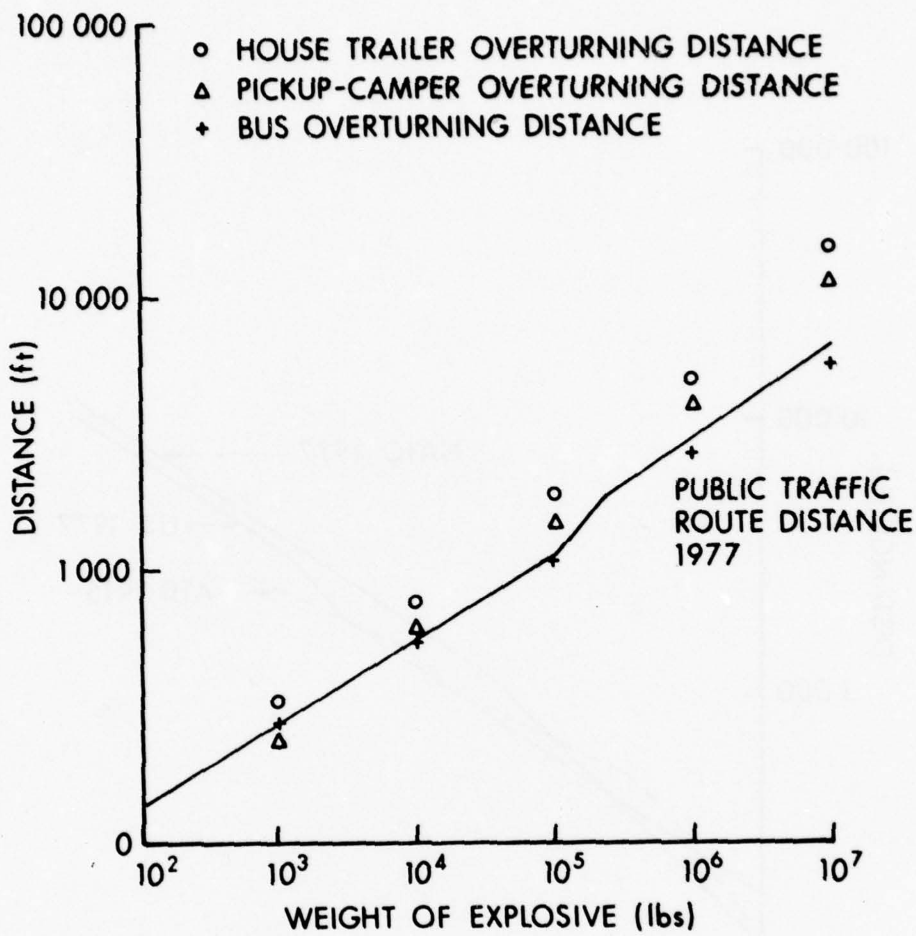

Figure 4. Comparison of 1977 Public Traffic Route Distance to Overturning Distance for Three Vehicles Computed using Falcon Pressure-Impulse Loading

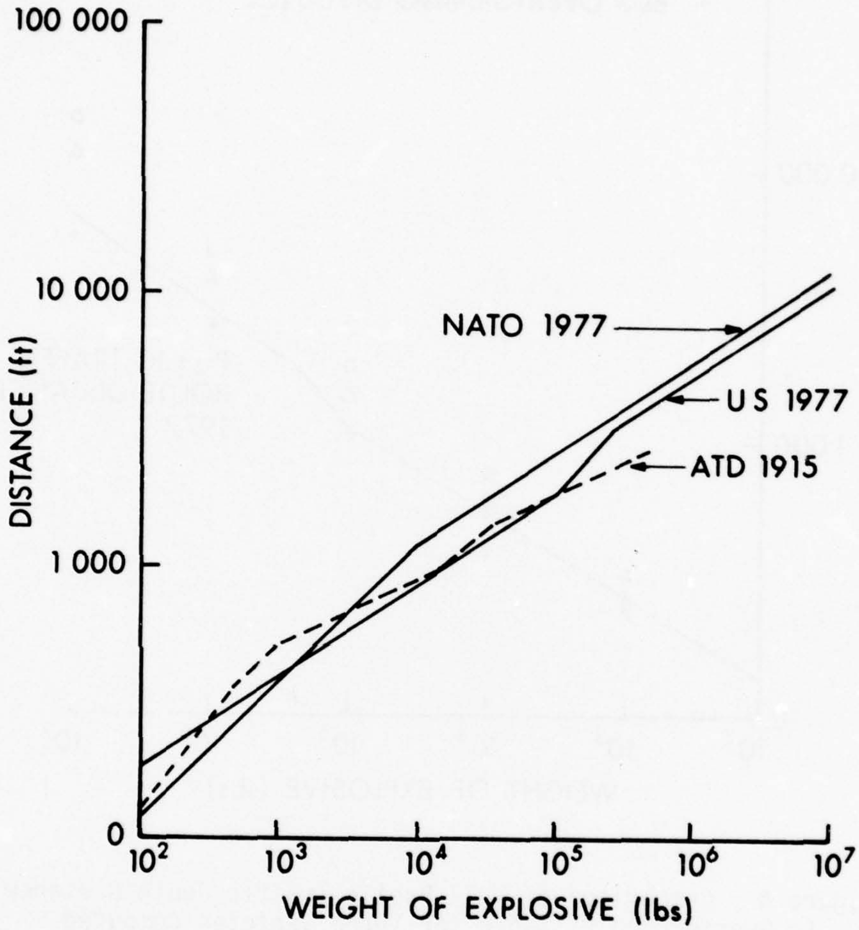

Figure 5. Comparison of the NATO and U.S. 1977 Inhabited Building Distances. Also shown is the 1915 American Table of Distance for a barricaded source.

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ESTIMATION OF EXPLOSION DAMAGE TO URBAN STRUCTURES IN THE NETHERLANDS

by

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Abstract

As part of the work that is performed in a study concerning the risks that are involved in storage of explosive goods, estimations have been made of the damage that might occur to urban structures in case of an accident. These estimations determine the probability that a certain damage to a structure, or structural element, will occur as a function of some blastwave parameters. The structures involved in this study are primarily urban structures consisting of load bearing walls with various structural elements such as brickwork partition walls, prefabricated concrete panels, windows, doors, structural steel elements and roof structures. For the charge weights and distance combinations examined, the relevant blast parameters appear to be peak overpressure and pressure risetime. It appears to be possible to produce damage charts for each element involved which give the probability of percentages of damage as a function of peak pressure at the indicent shock wave. However, additional information and new data is needed for further verification. It is also recognized that other aspects, such as induced groundshock and dangers for human beings that are hit by fragments of damaged structural elements, are also important in a hazard analysis.

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LIST OF SYMBOLS

W	charge weight
R	distance
t_+	positive duration
P_{so}	peak side - on pressure
T	natural period
$F(t)$	load function
x	displacement
x_v, x_u	yield and ultimate displacement
$\hat{F}/kx_v = \overline{F}$	dimensionless peak value of the loading
$t/T = \overline{t}$	dimensionless time
t_d	duration of the loading
$D_u = x_u/x_v$	ductility ratio
t_p	risetime, of the loading
P_{bs}	static pressure causing buckling of a compression arch
E	Young's modulus
h	thickness of the wall panel
R'	radius of the compression arch

I. INTRODUCTION

Recently, a new method of analyzing and judging dangerous situations and activities such as in traffic, transportation of LNG, storage of explosive goods, etc. has been developed. This method is called risk analysis, and the main objective of this method is to examine the effect of a failure in these situations or activities as well as the probability that such an event will happen. In a recent contract, the TNO-PML laboratory has performed a study of the hazards involved in the storage facilities of explosive materials. In particular, the project team studied the risks for people living near or passing by an ammunition storage area[(1)†].

Fig. 1 is an example of a damaged storage building and Figs. 2 and 3 are examples of these hazardous situations. From the photos, one can visualize the problems which can arise in the Netherlands--that is, roads and habitated buildings near explosion hazards. Until now, there have not been accidents in the aforementioned situations, but accidents have occurred with old World War II charges, with other disapproved charges, and in propellant production facilities. Fig. 4 is an example of such an accident and gives a map of recorded damage caused by an explosion in a propellant plant. Before going into the details of the damage estimation, explanation will be given on other items that have been investigated and the overall scheme in which they are placed (Fig. 5).

Concerning structural damage, there exists a need to know, as a function of some blast parameter, the probability that a certain kind of damage to a structure or structural element will occur. For example, a structural element like brickwork will have a low probability of complete failure in a blast field with incident peak overpressure of 15 kN/m^2 but will have a high probability of minor damage (such as cracking) in the same blast field. To illustrate the meaning of different damage percentages Figures 7, 8 and 9 are added which give varying brickwork damage. Figures 10 and 11 are illustrations of corrugated steel and reinforced concrete failures.

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† Superscript numbers in parentheses designate References at end of paper.

Figure 1. Damaged storage building of explosive goods. (Arch no. 780821)

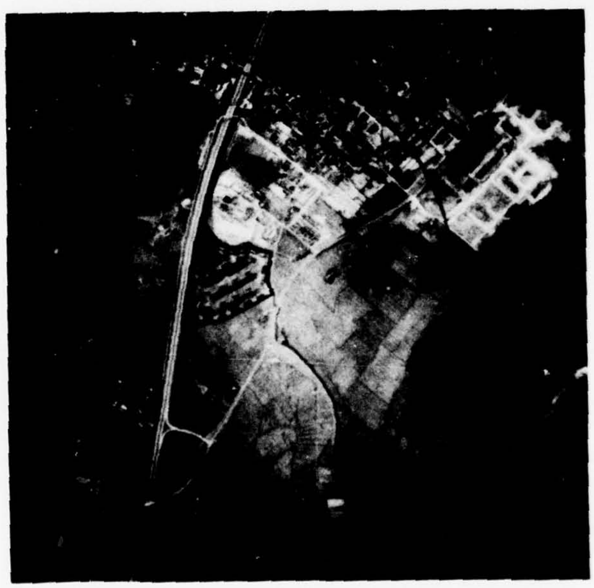

Figure 2. Example of a hazardous situation: ammunition storage near a highway and an urban area. The circle represents the required safety distance according to NATO regulations. (Arch no. 780819)

Figure 3. Example of a hazardous situation: ammunition storage near to one of Holland's major canals. The circle represents the required safety distance according to NATO regulations. (Arch no. 780817)

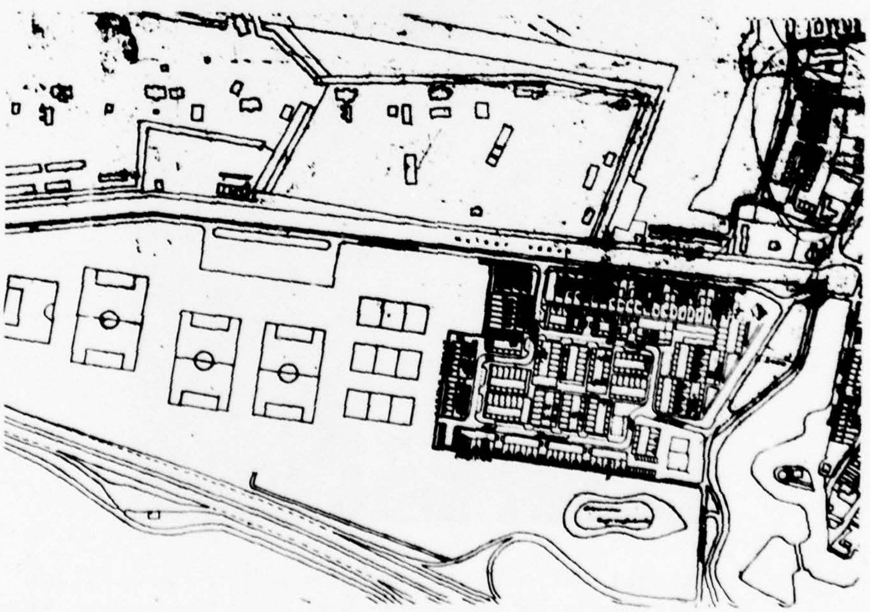

Figure 4. Map of reported damage caused by an explosion in a propellant plant. The cross is the explosion center, black spots are registrated damages. Notice the soccer fields for scale. (Arch no. 780822)

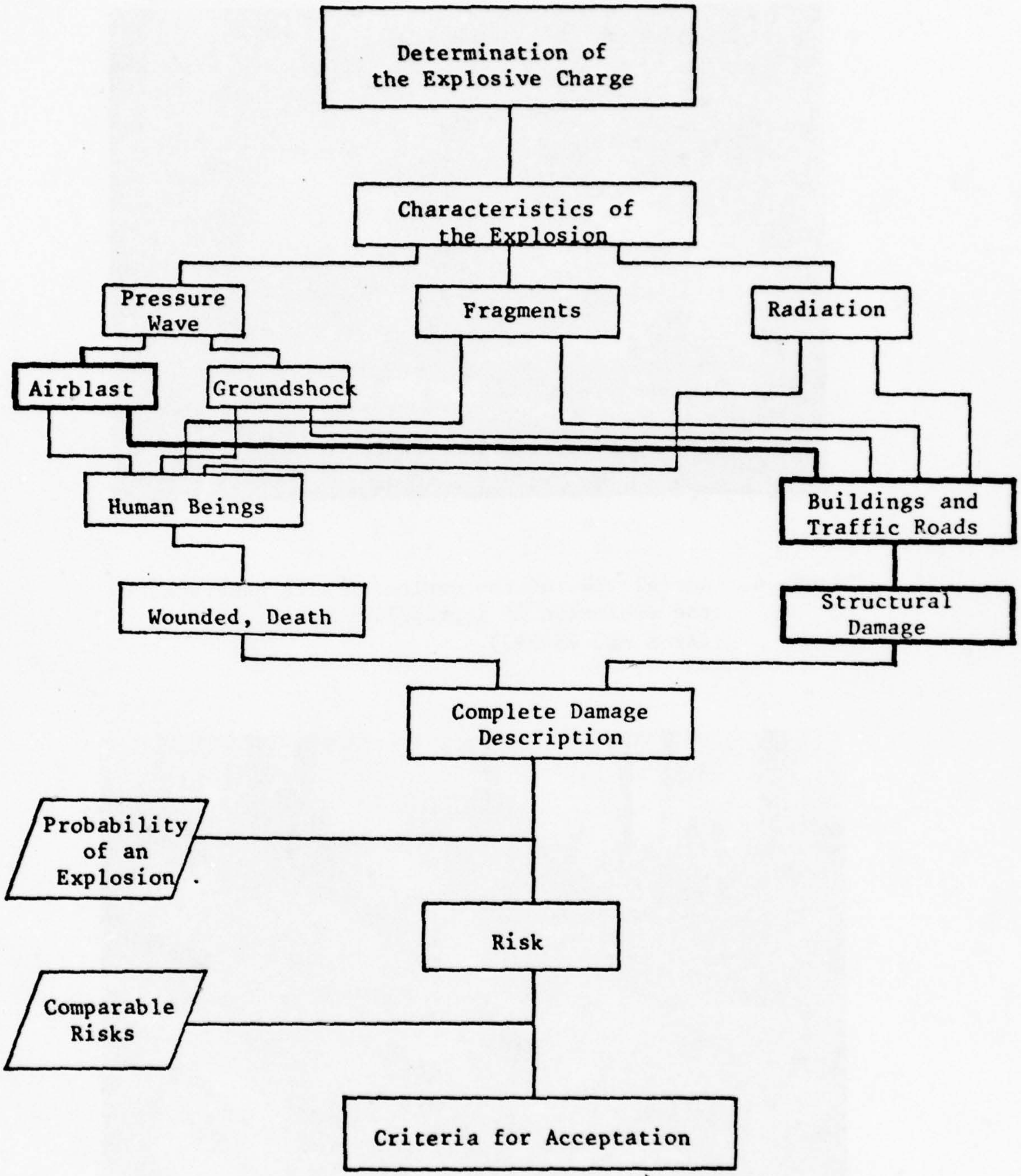

Figure 5. Overall scheme of the performed risk analysis.

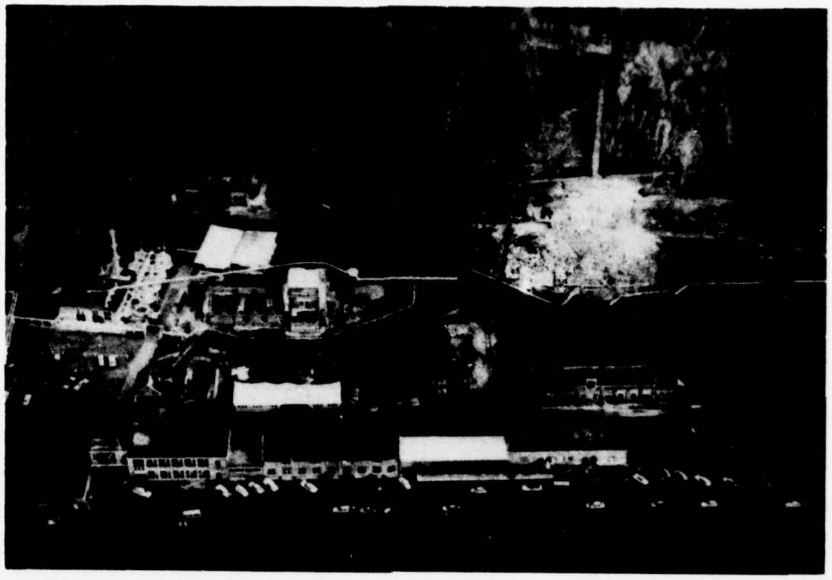

Figure 6. Aerial view of the explosion site generated by the explosion in a propellant plant. (Arch no. 750297)

Figure 7. Example of brickwork damage: complete demolition. (Arch no. 740937)

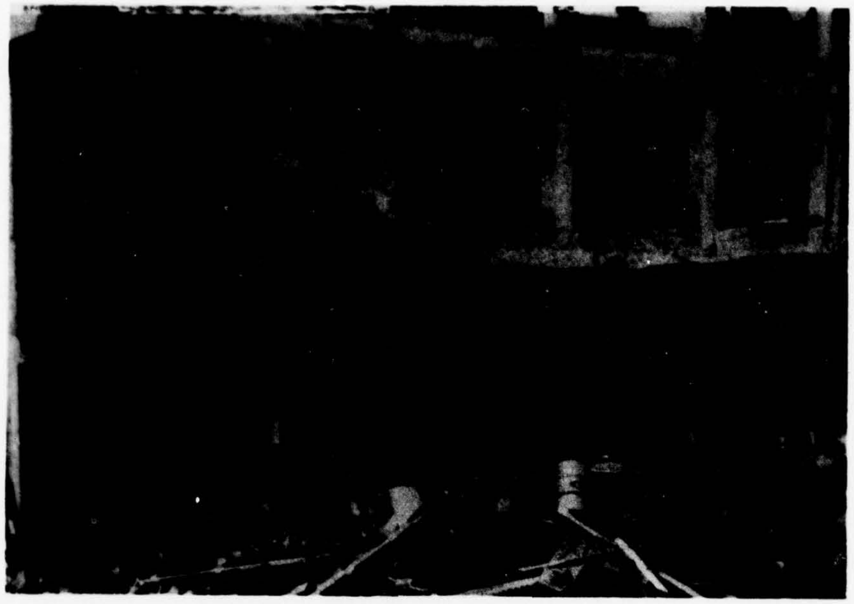

Figure 8. Example of brickwork damage: major parts blown out. (Arch no. 750372)

Figure 9. Example of brickwork damage: cracking. (Arch no. 780820)

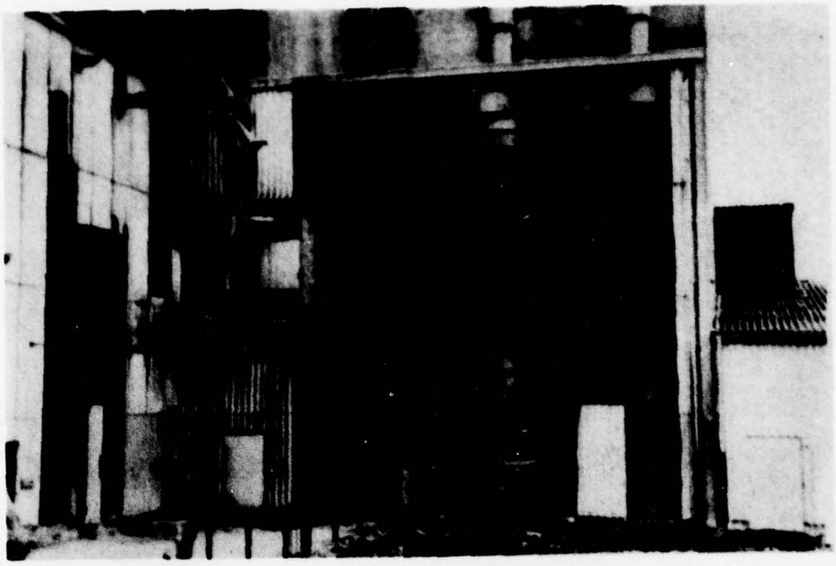

Figure 10. Example of damaged corrugated steel plates. (Arch. no. 750830)

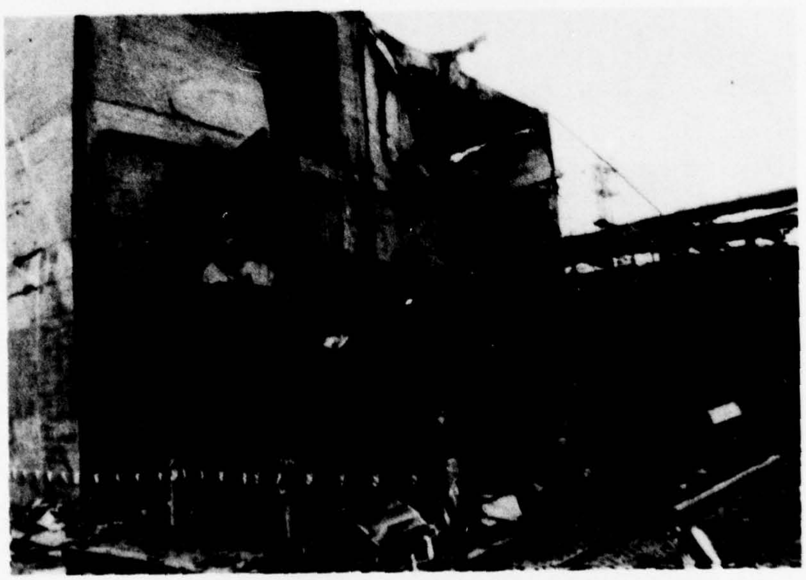

Figure 11. Example of damaged reinforced concrete slabs. (Arch no. 760306)

II. URBAN STRUCTURES IN RELATION TO EXPLOSION HAZARDS

As previously mentioned, consideration has been given in this study to the effect of an explosion of stored explosives in the vicinity of urban structures. Urban structures in the vicinity refers to residences, flat apartments, and farm houses at distances of 1000 m or more. Not all of these structures are composed of a load bearing main structure containing other structural elements such as curtain walls, glass panels in steel frames, etc. In fact, most of these structures consist of load bearing walls with structural elements such as brickwork partition panels and prefabricated concrete front panels. For the estimation of damage, considerable attention should be given to the behavior of the structural elements.

One can make a significant simplification when studying the behavior of structural elements and building frames loaded by shock waves coming from an explosion of the kind considered in this report. While the equivalent TNT charge weight of these kinds of explosions varies from 10,000 to 40,000 kg and the distance from 300 to 500 m, it can be derived[(2)] that the minimum value of the positive phase duration will be 0.16 sec. That is, for W = 40,000 kg and R = 300 m:

$$E = 1.8 \times 40{,}000 \times 4.516 \times 10^6 = 3.25E11 \text{ Nm}$$

$$\overline{R} = R \sqrt[3]{P_o/E} = 300 \sqrt[3]{1E5/3.25E11} = 2.025$$

$$\overline{T}_s = 0.365 = T_s a_o \sqrt[3]{P_o/E}$$

$$t_+ = \overline{T}_s/a_o \sqrt[3]{E/P_o} = 0.365/340.3 \sqrt[3]{3.25E11/1E5} = 0.16 \text{ sec}$$

The durations are relatively long compared to the short response times of the structural elements being considered. In the following section, the

influence of this large t_+/T ratio will be derived by means of a theoretical model and other blast wave characteristics which determine the response of the structures and the possible damage will be investigated.

Other aspects that have to be taken into account are reflection as a function of angle of incidence and the actual loading on the structure composed of loads at the front and back side of the structure in which building dimensions and shock wave speed are important parameters. Because these aspects are sufficiently described in handbooks, they are not further treated here.

III. STRUCTURAL DYNAMICS

As stated previously, the influence of the t_+/T ratio and other blast characteristics such as waveform and rise time will be examined by means of the simplest calculation model available--a single degree of freedom model[3].

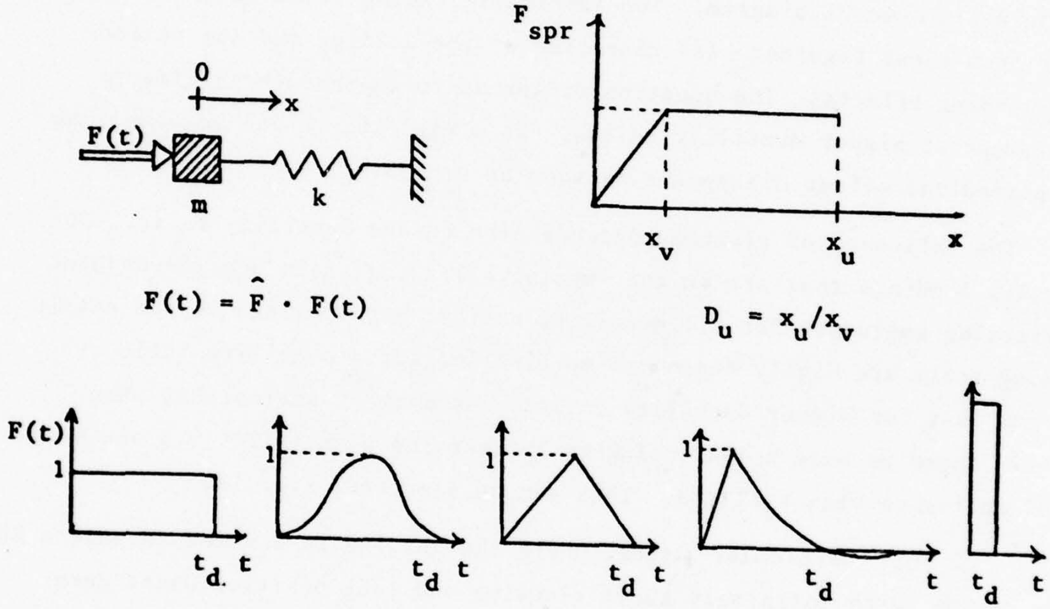

Fig. 13 - Single degree of freedom model with possible load functions

The differential equation that describes this problem is:

$$m \frac{d^2x}{dt^2} + kx = F(t)$$

which becomes:

$$\frac{d^2\bar{x}}{d\bar{t}^2} = 4\Pi^2 \{F(\bar{t}) - \bar{x}\} \text{ for } 0 \leq \bar{x} < 1/\bar{F}$$

$$\frac{d^2\bar{x}}{d\bar{t}^2} = 4\Pi^2 \{F(\bar{t}) - \bar{x}_v\} \text{ for } \bar{x} \geq 1/\bar{F}$$

by substitution of: $\bar{t} = t/T$, $\bar{x} = x\ (k/\hat{F})$, $\bar{F} = \hat{F}/kx_v$[5].

By numerical solution, the displacement $\bar{x}(t)$ can be found and can be related to the ultimate displacement[4].

In Fig. 14, combinations of peak value $\hat{F}/kx_v$ and duration t_d/T are shown for these load functions which produce a maximum displacement equal to the yield displacement: $D_u = 1$. Fig. 15 gives the same result plotted in the well known PI diagram. Two important loading parameters become clear from these figures: (a) rise time of the loading and (b) periodical loading effects. The question arises as to whether these effects also occur at higher ductility ratios. From Fig. 16, it can be seen that the periodical effect disappears as soon as $D_u > 3$.

The influence of risetime depends also on the ductility ratio. Obviously, loadings that are in the impulsive loading realm are independent of risetime influence for all ductility ratios; but loadings in the static loading realm are highly dependent on risetime for a ductility ratio of one and less for higher ductility ratios. Newmark[5] states that when $D_u > 2$, there is only a 10% influence by risetime when $t_p/T < 0.5$ and only a 30% influence when $t_p/T < 3$. This can be seen from Fig. 17.

For this particular study, where the loading is assumed to have a shock wave shape with infinitely short risetime and long positive phase duration, it appears that the critical parameter for damaging structural elements is the peak value of the applied load. Comparison can be made with the static design loading taking into account reflection with a reflection coefficient of about 2 and infinitely short risetime giving a dynamic load factor of 2.

■ = block shaped load

● = sinusoidal load

▲ = triangular load

◣ = typical blast wave load

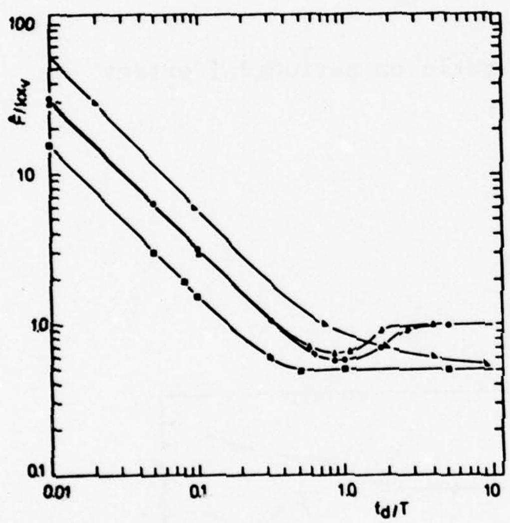

Fig. 14 - Combinations of peak value and duration producing D_u ratio equal to one

(Arch.no. 780823)

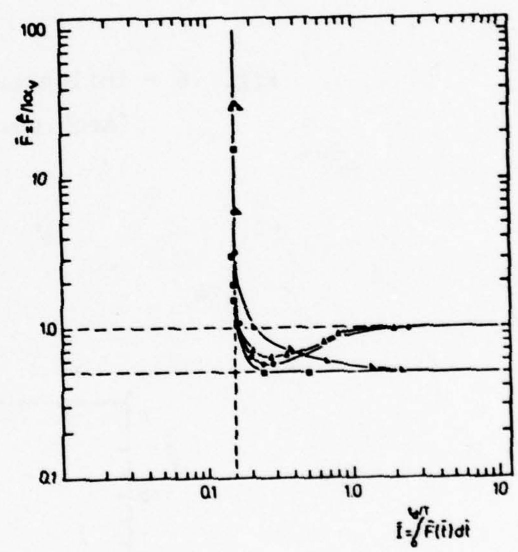

Fig. 15 - P.I. diagram of loadings producing D_u ratio equal to one

(Arch.no. 780824)

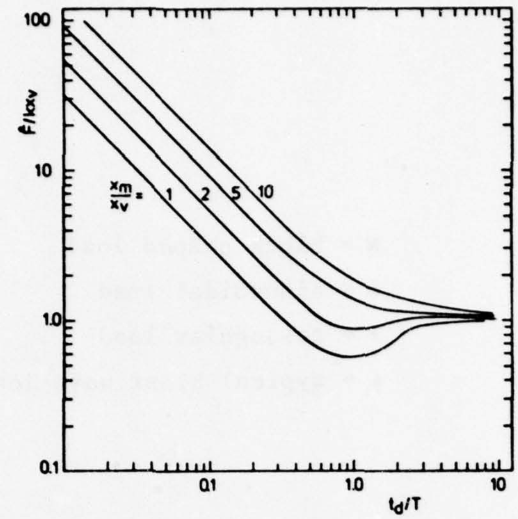

Fig. 16 - Influence of D_u ratio on periodical effect (Arch.no. 780825).

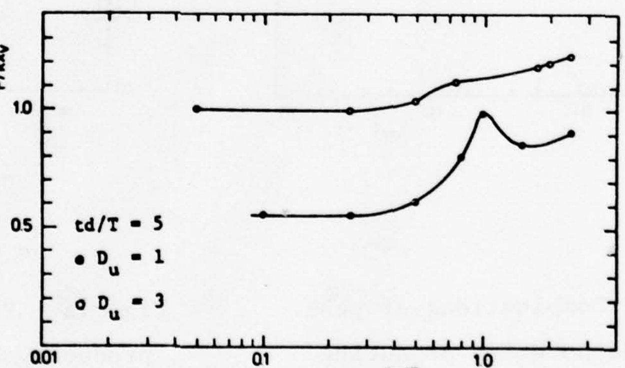

Fig. 17 - Influence of risetime on required resistance at several D_u ratios (Arch.no.780826)

IV. PROBABILITY OF DAMAGE

As previously mentioned in the introduction, the need exists to know as a function of a blast parameter (such as peak overpressure) the probability that certain kinds of damage to an element will occur. Fig. 18 is an illustration of this need. As far as we know, only one reference gives probabilities of damage, based on a comprehensive study[(6)]. This work of Pickering and Bockholt of SRI is only partially usable for this study because the building types are different and because a probability is given for only one kind of damage. For instance, they give the probability of 75% damage to roof structures of several kinds of buildings.

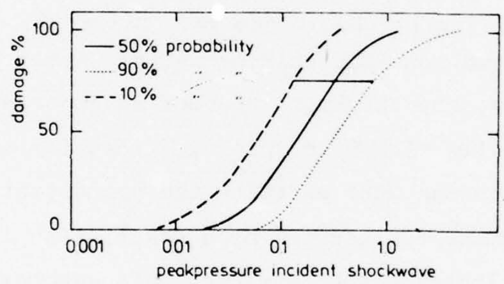

Fig. 18 - Damage probability diagram
(Arch.no.780827)

Another source for this study has been the several papers presented at previous Explosive Safety seminars giving results of explosion tests on structures where the blast field and damage have been recorded[(7)]. Also, test results of wall panels in blast simulators such as the ones reported by Wilton, Gabrielson, and Kaplan for URS Research Company have been used[(8)]. Finally, an estimation has been made of upper and lower boundaries; that is, 100% probability of complete demolition and 0% probability of no visible damage. The last boundary can be related to design loads such as wind, taking into account load factors.

V. AIRBLAST DAMAGE CHARTS

As far as possible, these data have been used to make damage charts for the structural elements considered. These were: concrete and brickwork walls, corrugated steel and asbestos cement plates, roofs, windows, and doors because these elements will occur in most of the urban areas encountered. Damage curves for the aforementioned structural elements appear in Figs. 19 through 24. The author does not propose that the entire damage description can be made exactly by means of these charts. Nevertheless, any estimation better than rules, such as those shown in Table 1, is worthwhile. The charts contained in this paper are not yet complete. Extensions must be made for other elements and more data should be obtained for a better foundation of these charts.

The problems that arise when processing the available data can be illustrated by considering brickwork damage. Distinction must be made between load bearing and non-load bearing walls. After restriction to non-load bearing walls, the thickness becomes an important parameter: 11 cm, 22 cm, or two 11 cm walls with 6 cm spacing. Then for a 22 cm wall, data are available[9] with which one must estimate the appropriate percentage of damage and probability of damage represented by a description like "slight cracking and deflection." In Table 2, the result of this estimation is given for 22 cm brick panels with no openings. In Fig. 25a, these values are plotted in the damage-probability diagram. A lower boundary can be estimated from a wind loading[10] of 1.0 kN/m^2 which makes $P_{so,0\%} = 0.45 - 0.50$ kN/m^2 with a low probability. An upper boundary can be estimated with the following formula which is derived for buckling of a cylinder[11] (Fig. 26)

$$P_{bs} = 0.861\ (Eh^2/R'L) \sqrt{h/R'}$$

where, in this case, the cylinder is formed by the compression arch in the wall panel. This leads to the upper boundary for $P_{so,100\%}$ of 45 kN/m^2 and 200 kN/m^2 for wall heights of 3.6 and 2.4 m, respectively. These values are given in Fig. 25b.

□ Δ ◇ = solid brickwork, 8"

◆ = solid brickwork, 4"

■ = brickwork, 4" and 8" concrete blocks with 2" spacing

○ = probability for all load carrying brickwork walls

● = probability for panel and curtain walls

▲ = probability for panel and curtain walls with no openings

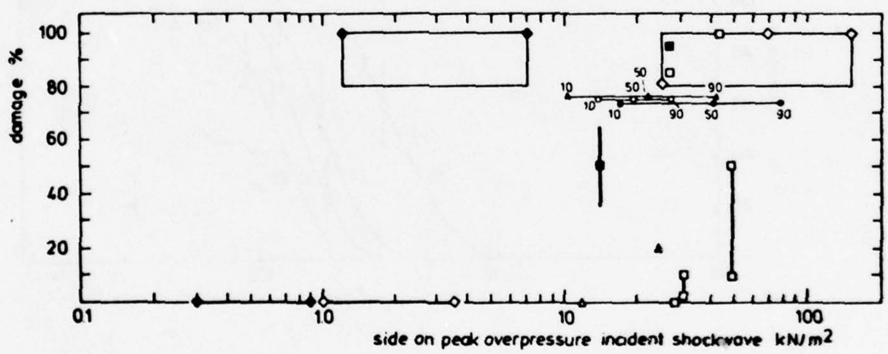

Fig. 19 - Damage chart, brickwork

(Arch.no.7709102-3)

◇ = wall, thickness 0.15 m

Δ = wall, thickness 0.20 m

o = panel, thickness 0.20 m

□ = wall, thickness 0.25 m

+ = wall, thickness 0.30 m

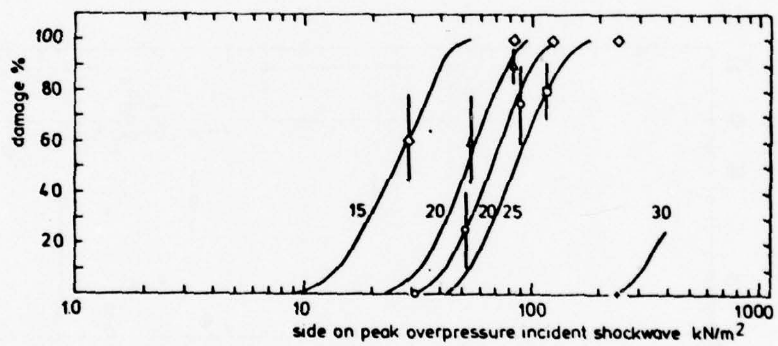

Fig. 20 - Damage chart, concrete walls
(Arch.no. 7709103-3)

o = probability of damage for corrugated panels of steel and asbestos cement

Δ = corrugated steel

□ = asbestos cement panels

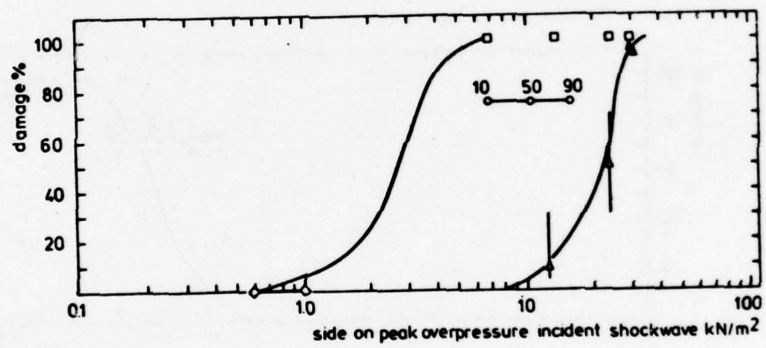

Fig. 21 - Damage chart, corrugated panels
(Arch.no. 7709104-3)

□ = probability of 75% damage, peaked wooden roof with tiles

Δ = probability of 75% damage, flat roof built up

× = probability of 75% damage, flat concrete roof

o = wind loading

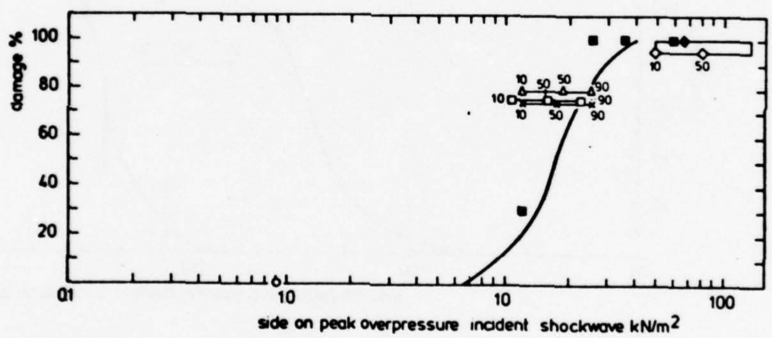

Fig. 22 - Damage chart, roof structures
(Arch.no.780828)

◇ = bheta distribution function, residences (6)
● = bheta distribution function, flat apartments (6)
× = bheta distribution function, tall office buildings (6)
△ = tall office buildings (9)
□ = residences (7)
○ = wind loading

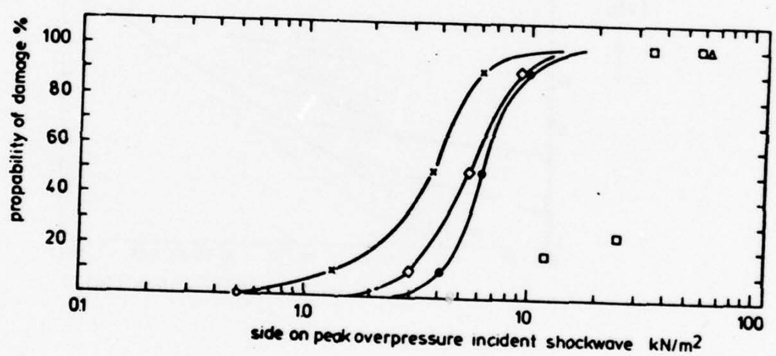

Fig. 23 - Damage chart, doors
(Arch.no.780829)

□,○ = data based on analysis of accidental propellant explosion using different explosive yields

◇ = data from I. W. Reed, Explosive Safety Seminar 1973

\+ = data based on analysis of accidental propellant explosion in 1963

x = TNO experiments on window panes

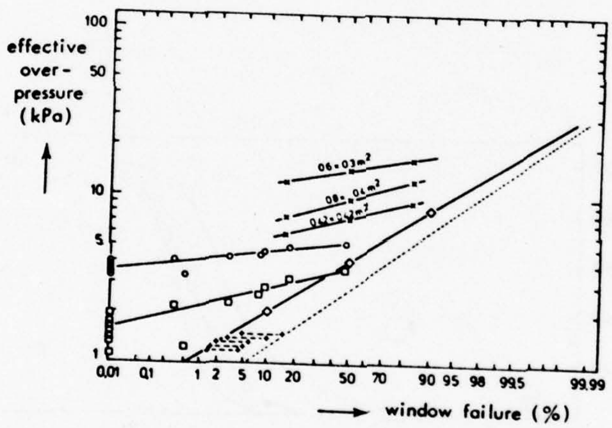

Fig. 24 - Damage chart, glass panels
(Arch.no.7709105-D)

□ = test data on 8" brickwork walls.

△ = estimated upper boundary from buckling

o = bheta distribution for a 75% damage

◇ = data from experiments

▲ = estimated lower boundary from wind loading

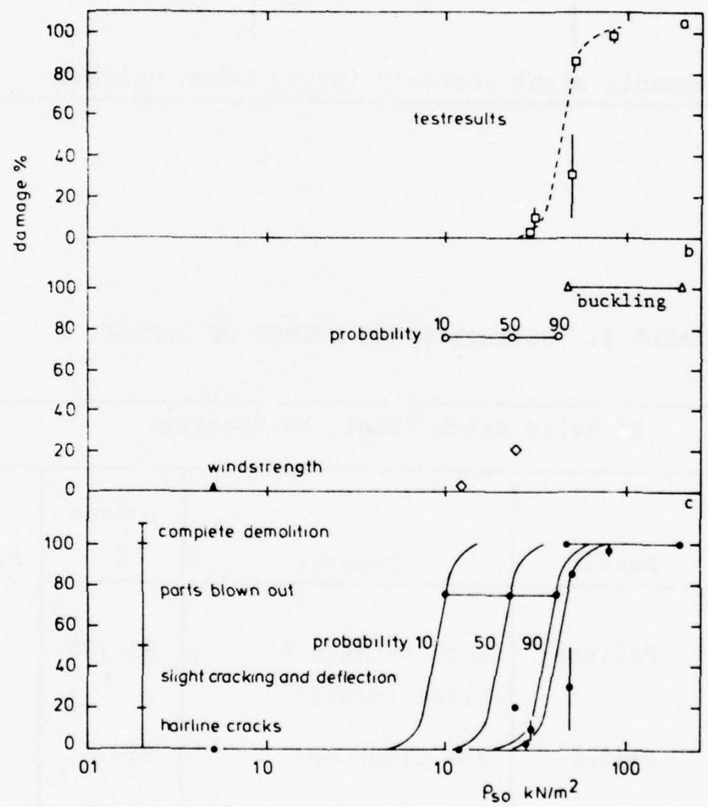

Fig.25. Generation of a damage chart by gathering all available data.

(Arch.nos. 780830-A, 730837-B, 780838-C)

TABLE 1. DAMAGE RULES

Damage Table Department of the Interior	Zone I Zone II Zone III	42 kN/m^2 14 kN/m^2 7 kN/m^2
Damage Table TNO/CTI	Badly Damaged Repairable Damage Window Breakage	P_{so} = 30 kN/m^2 P_{so} = 10 kN/m^2 P_{so} = 3 kN/m^2
Fragments might severely injure human beings.		

TABLE 2. ESTIMATION OF EXTENT OF DAMAGE

8" Solid Brick Panel, No Openings

P_{so} kN/m^2	P_r kN/m^2	Result	Remarks	Damage %	Probability
83	223	Failure	only fringes of brick remain	95-100	
52	127	Failure	85% blown out	85	
50	119	Damage	slight cracking and deflection	10-50	
31	70	Damage			
31	70	Undamaged	some spilling	5-15	
29	65	Undamaged	almost damage-free, hairline cracks	0-5	

As mentioned earlier, Pickering and Bockholt give probabilities of 75% damage to brickwork panels, curtain walls, or load-carrying walls for several kinds of buildings. For exterior walls with no openings, these values are:

10% probability for at least 75% damage, $P_{so} = 10.2\ kN/m^2$

50% probability for at least 75% damage, $P_{so} = 24\ kN/m^2$

90% probability for at least 75% damage, $P_{so} = 42\ kN/m^2$

Figure 25c is the final result where all the data points are gathered and correlated to each other.

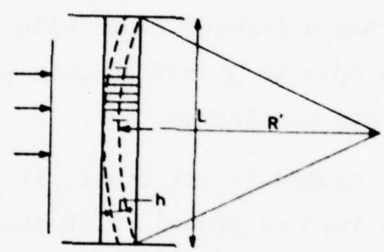

Fig.26.

(Arch.no. 780831).

VI. CONCLUSIONS AND FUTURE DEVELOPMENTS

Considering the previous material and facts, the only justified conclusion that can be drawn is that there must be some relation between damage caused by the blast wave and the probability that this damage occurs for each structural element. The relations that have been given in the previous text should be handled with great care. We feel that additional data are required to make them more general and give them more validity. Moreover, a very careful elaboration of old and new material should be made; and the relations presented above should not be handled as some kind of standard and completed guidance but as an approach of estimating and judging damage to urban structures caused by explosions. Yet, we believe that this approach has a future, especially in the Netherlands, where many activities can only be justified when probabilities of unwanted events and their effects are considered.

Besides the damage caused by air blast, it became clear recently that the damage caused by induced ground shock should not be neglected. Analyzing damage caused by an unconfined vapor cloud explosion in Beek, the Netherlands, it became obvious that the damage that occurred to a certain school building was not caused by air blast directly but by the induced ground shock. Other references[12,13] stated that damage to buildings in the region where air blast can be neglected can be caused by ground shock. Another development for the future may be that in civil engineering sciences, a probabilistic approach may become popular and will enable us to calculate probabilities of failure, incipient failure, minor damage, and no visible damage. Since this study is not yet completed and will not be completed in the near future, we feel that a call for information, references, data, and critics is the best approach. Possibly, a data bank on this subject can be set up which would work with defined approaches and judging rules.

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RECENT EUROPEAN EXPERIMENTS ON Q-D CRITERIA

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SUMMARY

1. This paper discusses recent trials at model and full scale involving experimental explosions and deflagrations sponsored by France, the Federal Republic of Germany, Norway, Sweden, Switzerland and the United Kingdom. The ramifications for tables of explosives Quantity-Distances (Q-Ds) and future designs of buildings are indicated briefly.

INTRODUCTION

2. The theme of this presentation is the asymmetry of explosions and deflagrations in practical situations and the effort being expended in Europe to measure the directional effects in order to take them into account when assessing quantity-distances.

3. There is nothing new in the observation that most explosions and fires display a marked lack of symmetry. For many decades this effect has been taken explicitly into account in some fields, for example in the Q-D Tables for Igloo magazines. In most fields however national explosives safety authorities have held the view that it would be too complicated to apply different distances in different directions in azimuth around a Potential Explosion Site. The Q-D Tables have therefore been based on gross simplifications of the phenomenology of explosions and deflagrations.

4. The resultant simple, neat safety circles are a luxury that few countries now can afford. Encroachment of safeguarding zones external to explosives facilities and the need to intersperse new magazines or workshops among existing ones inside these facilities create a demand for reappraisal of Q-D criteria with the aim of removing constraints on land utilization.

Q-D CRITERIA FOR EXPLOSIVES OF DIVISION 1.1

5. The NATO Manual on underground storage of explosives gives some indication of the variation of blast intensity with azimuth around an adit but recommends that in general model tests be conducted to determine the 50 mb isobar corresponding to a particular geometrical configuration.

6. Figure 1 illustrates the sort of hillside magazines which have been studied recently by the Federal Republic of Germany, Norway and Sweden (references 1, 2, 3). This is a situation where it would be absurd to draw a safety circle with uniform radius. The problem is to determine how the blast falls off as one leaves the forward direction where there is

pronounced jetting through the adit. These tests, mainly at small model scale but validated by some testing at a large scale, give information on the attenuation achieved by the "Swedish Block" device and a comparison with a surface explosion (Figure 2), as well as the variation of adit blast with azimuth (Figure 3). Figure 4 illustrates the importance of the reduction achieved by the block device.

7. The firm of Basler & Hoffman, consulting engineers to the Swiss Federal Construction Service, has made a presentation already on hazard analysis of Potential Explosion Sites. Basler & Hoffman, in connection with this study, have sponsored tests in Sweden (reference 4). Figure 5 shows a slightly buried magazine with two chambers. It would be difficult to predict the isobars in the vicinity of such a structure. Experiments at a scale of 1:10 have enabled the isobars in Figure 6 to be constructed and also the lines of equal debris density shown in Figure 7. Debris dispersal is at least as important as airblast in assessing the hazards of such a situation.

Q-D CRITERIA FOR EXPLOSIVES OF DIVISION 1.3

8. Although the directional effect of a deflagration in a magazine has been known since 1946 (Figure 8), the authorities in many countries have until very recently persisted in applying safety circles to propellant stores. The Australian authorities noted the marked effect of the wind during an accidental deflagration (Kingswood, NSW, 1971) and carried out trials during 1976 to determine, among other matters, the effect of wind on heat field displacement.

9. The original United Kingdom trials, incorporated in the basis of the NATO criteria for Division 1.3, used mainly bulk propellant as in Figure 9. Clearly the burning rate would be very different in the case of pallets of packages containing the propellant, as was used in the Australian trials. The United Kingdom has recently performed trials using packaged propellant on pallets (reference 5). Some packages were fibreboard; in other tests they were wooden boxes. The fires were started inside a concrete structure simulating the confinement of a real magazine. Directional jetting was expected but the extent of the flame jets surprised the observers (Figure 10).

10. The French authorities have been interested in the directional effects from certain types of magazines for propellants and have conducted trials at the Centre d'Essai des Landes, Captieux Range (reference 6). The design of the structure created marked directional effects in the preferred direction and the wind also had some effect (Figure 11). The French authorities intend to exploit this directional effect to prescribe reduced Q-Ds to the rear and sides of such a structure.

Q-D CRITERIA FOR EXPLOSIVES OF DIVISIONS 1.2 & 1.4

11. The dominant hazard from explosives of Division 1.2 is, by definition, the hazard from projections. There is at present some discussion internationally as to how one should interpret the UN definitions for Divisions

1.2 and 1.4 in order to distinguish "a projection hazard" from "no significant hazard." Since regulations may prescribe a separation of 25m between buildings "to prevent ignition by radiant heat" (NATO Manual), this distance may be useful in establishing a quantitative criterion of a significant projection hazard in storage.

12. The United Kingdom began this year a series of tests to gather data on the projection hazard from items hitherto classified in Division 1.2 or 1.4. The tests follow the UN Recommendations for an External Fire, Stack Test. The area is surveyed after each fire to measure the dispersal of projections following the procedure originally described by US Naval Proving Ground Dahlgren in order to attain comparability of results. Figure 12 illustrates the sort of results which might be expected. In the storage situation, the hazard at 25m is a key factor. During transport, however, one is concerned with the hazard at a much closer distance, say 2 to 5 metres.

3. Witness screens have been introduced in the UK trials to obtain an indication of number and lethality of the projections with a limited range. Sheets of aluminium 1mm thick were erected in the vertical plane sited 2m from the centre of the fire. Although this risked damage to the sheets by flame on the downwind side, it was necessary to site the sheets close to the source in order to intercept a useful proportion of the projections without using extremely large sheets.

14. The first few tests have been conducted but many remain to be completed in order to collect information sufficient to establish beyond doubt the correct classification of many military and civil items of explosives, ammunition and pyrotechnics.

15. Already it has become evident that account should be taken of directional effects. Shaped charges in packages present an obvious example of the need to design a trial with due regard to asymmetry. Many pyrotechnics also are capable of exhibiting directional effects. It will be for consideration to what extent it is practicable to apply different Q-Ds in different directions taking account of the nature of the explosives, their packaging and possible structural protection during storage and manufacture.

RAMIFICATIONS FOR Q-D TABLES AND FUTURE DESIGNS OF BUILDINGS

16. The United Kingdom's Explosives Storage & Transport Committee of the Ministry of Defence has now adopted Q-D Tables (reference 8) which make explicit allowance for the reduction in hazard in certain directions, or alternatively for the increase in hazard in other directions, depending on the type of building used for storage or manufacture of explosives.

17. It will be interesting to see how this innovation works in practice. The saving in land in certain sectors will have to be weighed against the penalty of more complex administrative procedures to apply these asymmetrical Q-Ds. Other countries too are actively investigating the possibilities of

purpose built structures designed to exploit this asymmetry for the various types of explosion and deflagration hazard. It will be profitable to exchange experiences among nations, in respect of both the experimental results and the administrative problems involved.

CONCLUSION

18. It is concluded that many European countries are contributing by their experiments and ideas to the development of more sophisticated Q-D criteria and explosives buildings. Since the work is not confined to military explosives nor to the members of a military alliance such as NATO, it is useful to exchange information on these topics at an international conference which extends across the whole field of explosives safety technology. The DoD Explosives Safety Seminars are ideal for this purpose and it is hoped that this very brief indication of European experimentation will promote cooperation and avoid any unnecessary duplication of work.

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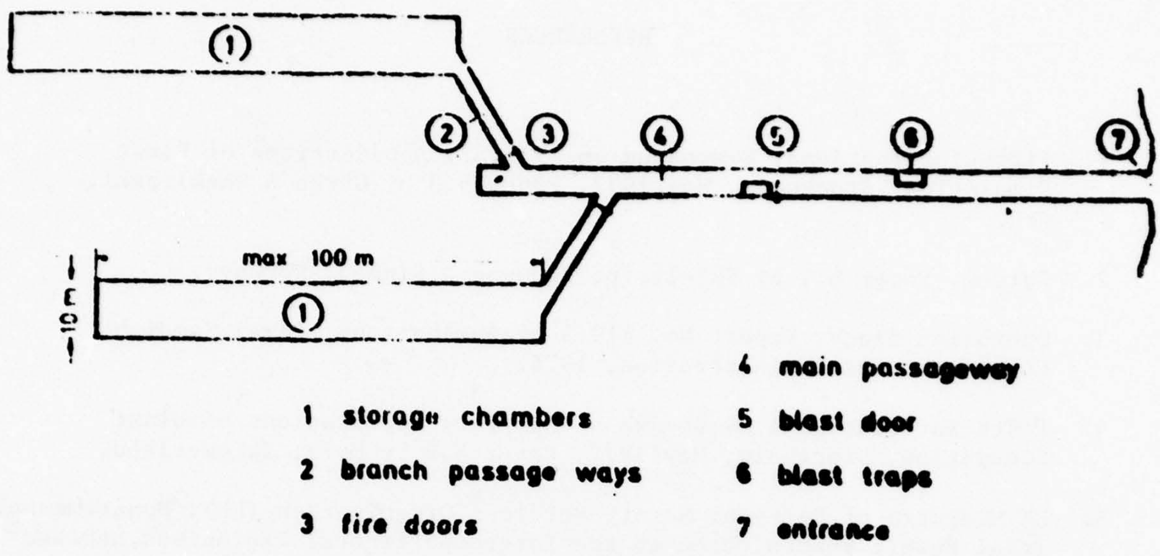
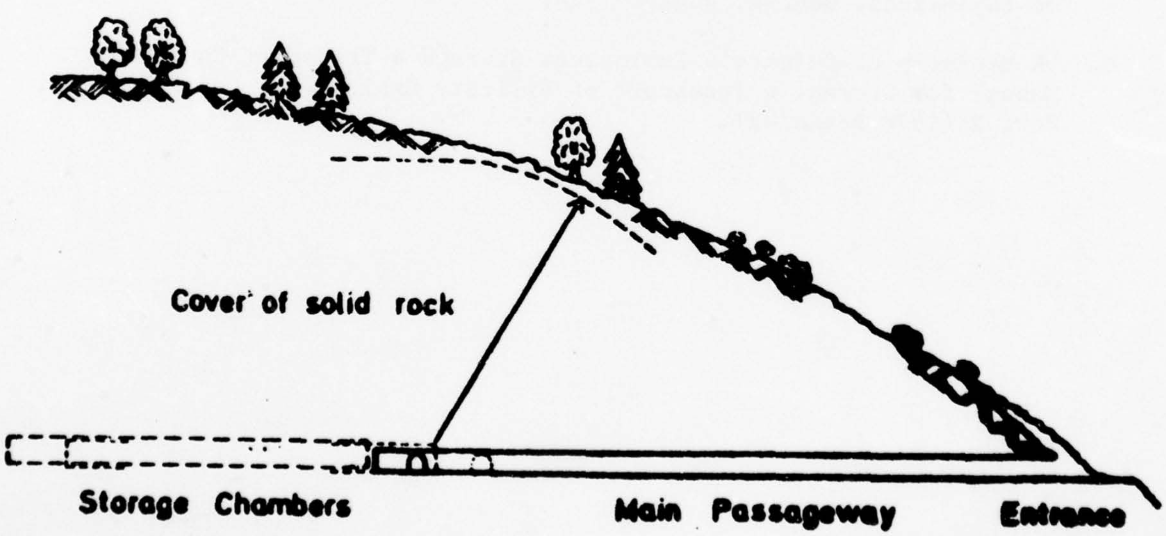
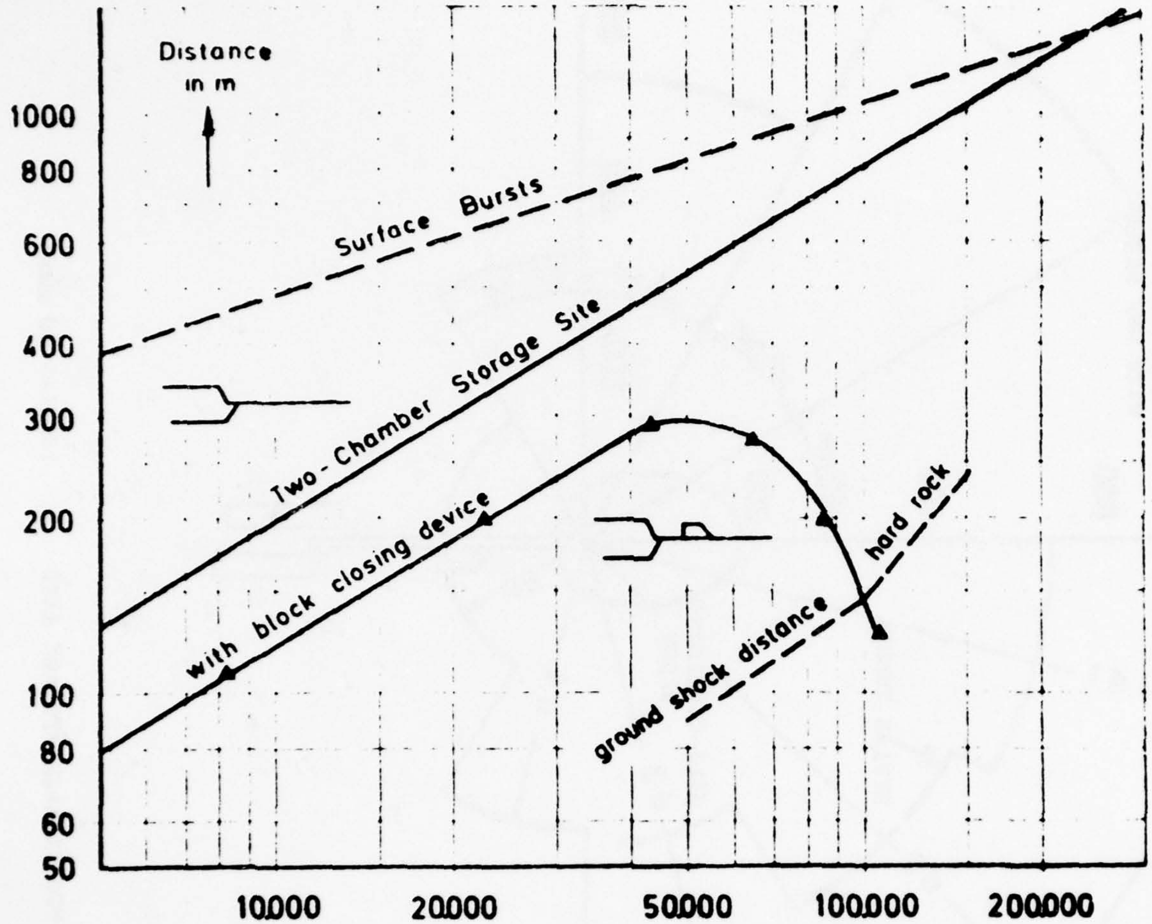


Two chamber storage site



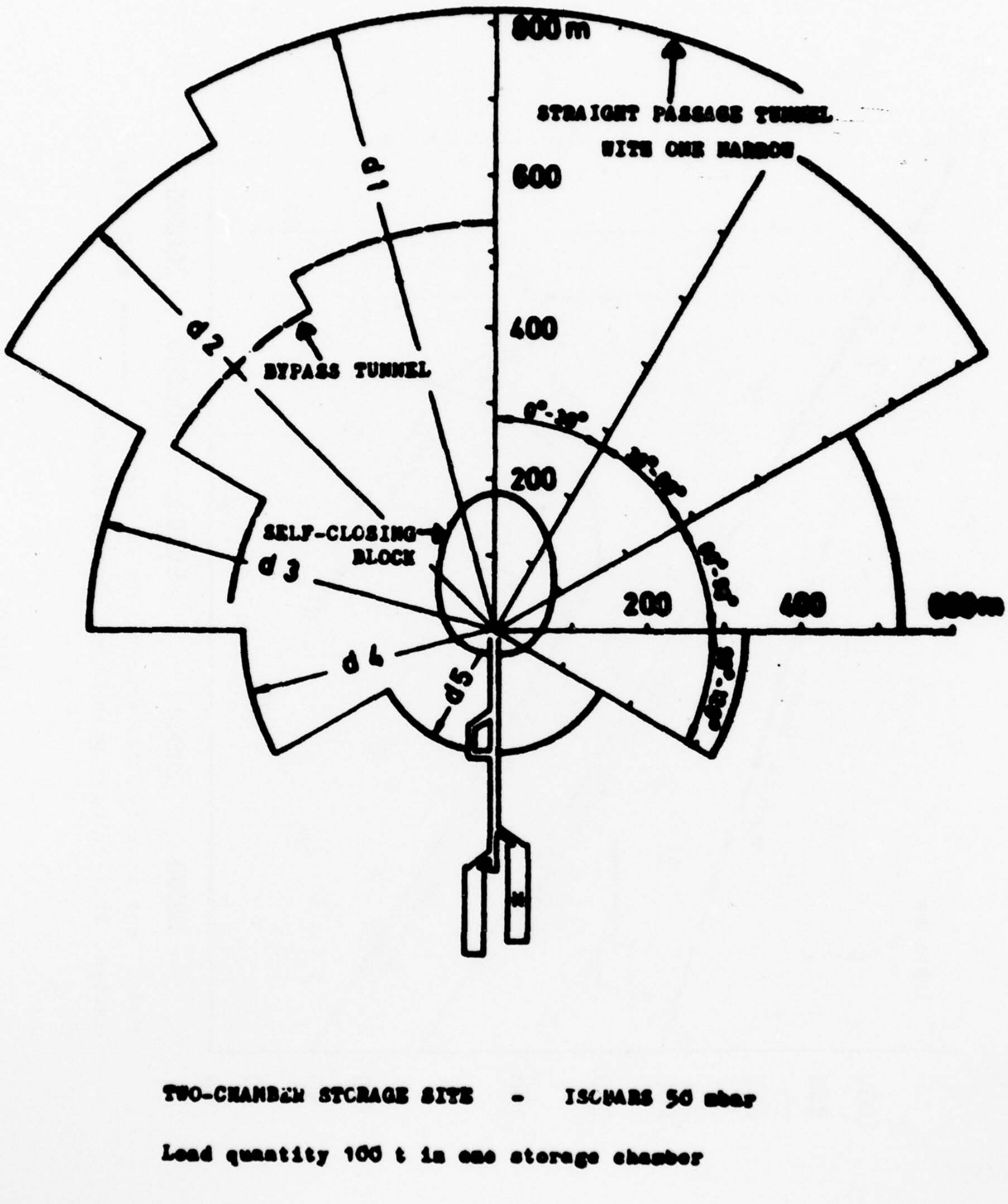
Cover for facilities built into hills

Figure 1



Model test results. Distance of the 50 mbar-isobar. Storage site with block closing device

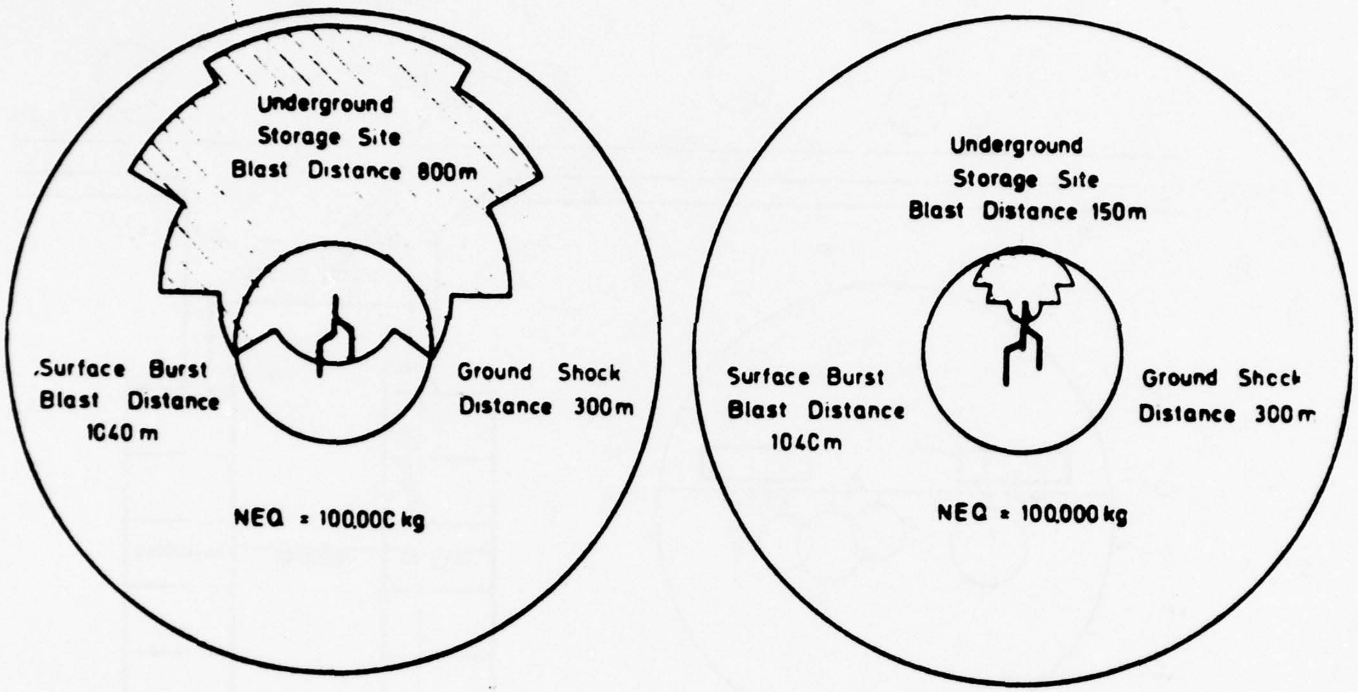
Figure 2



TWO-CHAMBER STORAGE SITE - ISOBARS 50 mbar

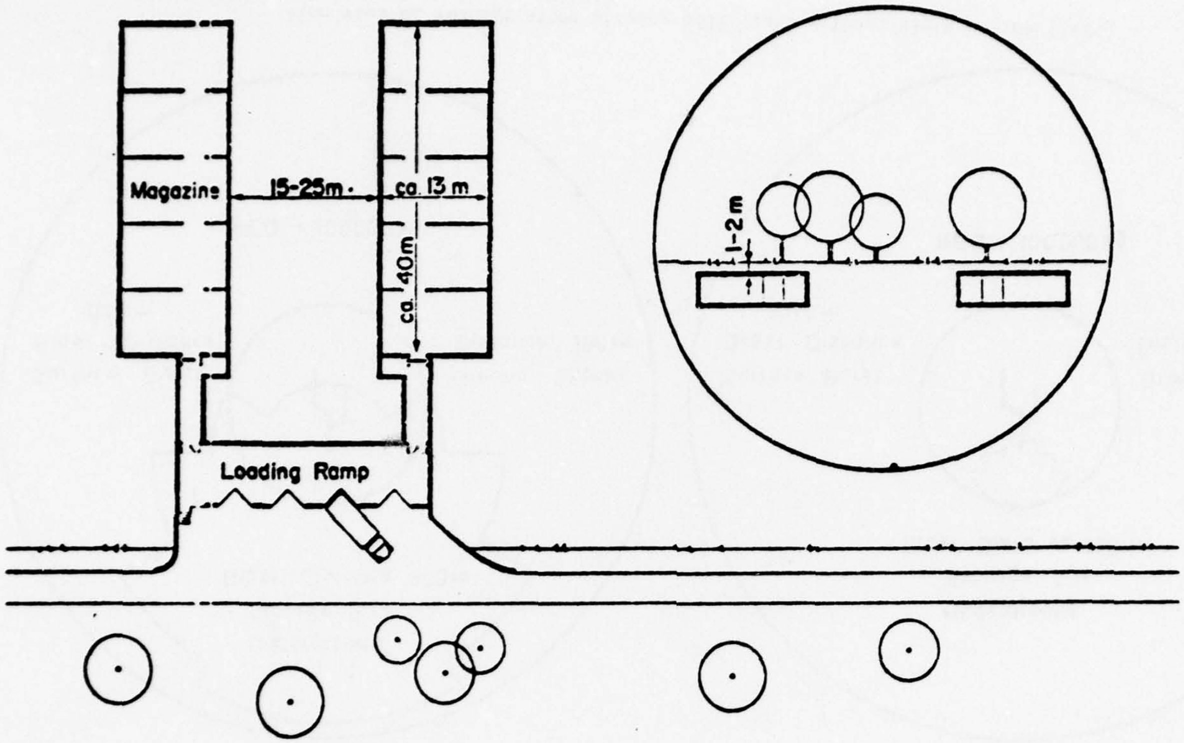
Lead quantity 100 t in one storage chamber

Figure 3



Plan view of storage sites showing adit blast without block device (left) and with block device (right).

Figure 4



Plan view and section of slightly buried concrete magazines (two-chamber system)

Figure 5

Isolines of peak pressures for model charges of 50, 30, 15 and 5 kg of TNT

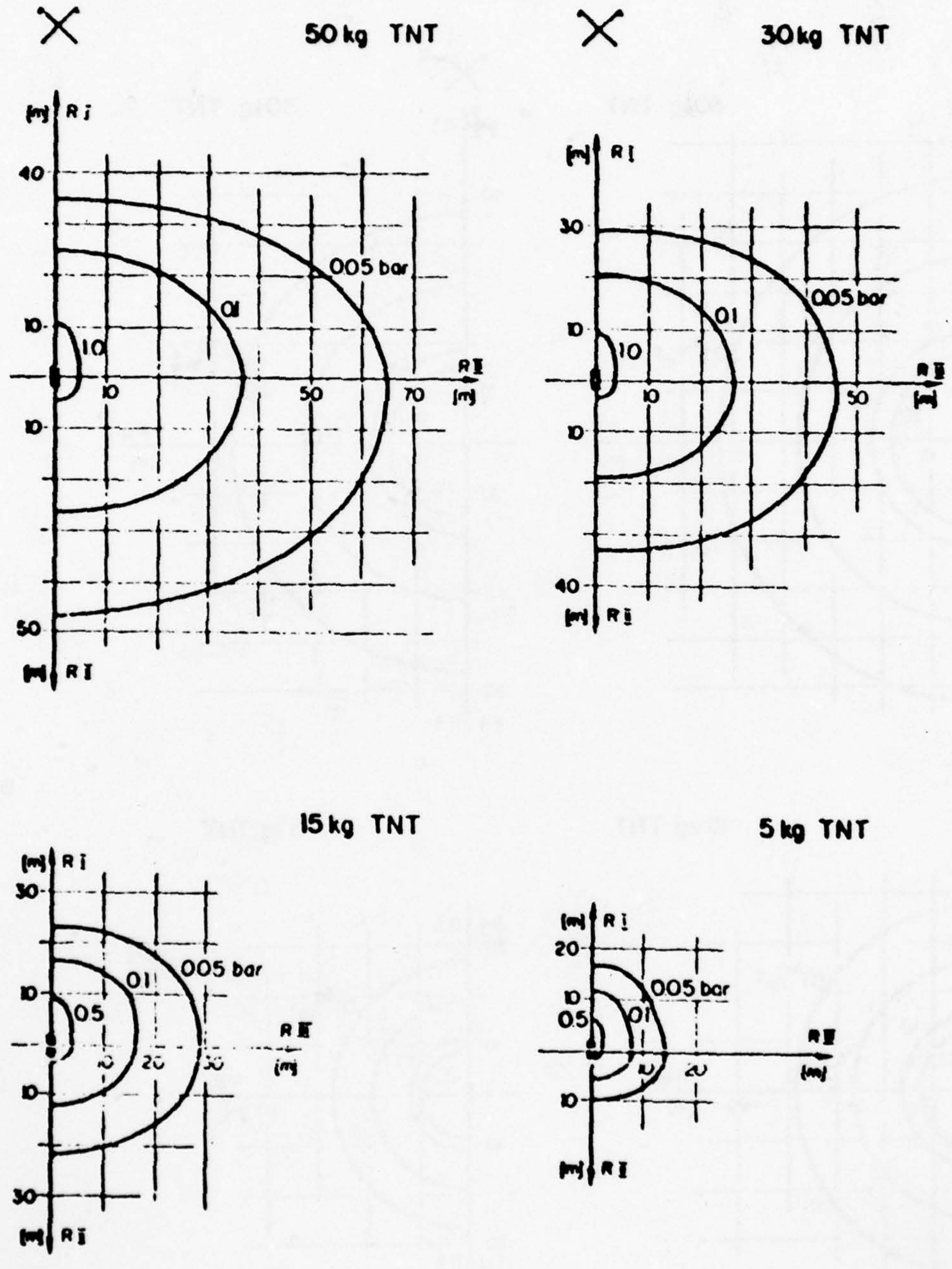


Figure 6

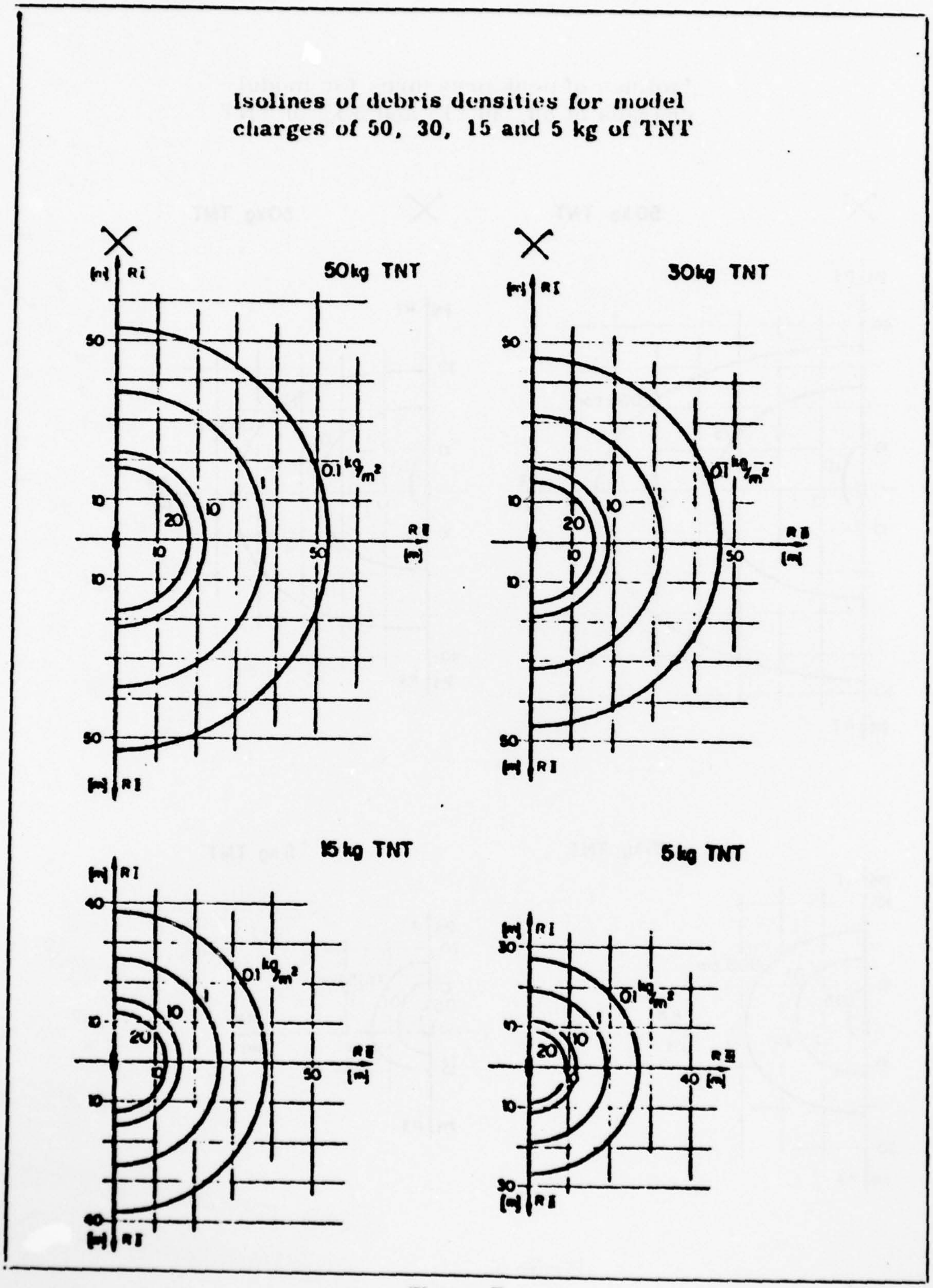

Isolines of debris densities for model charges of 50, 30, 15 and 5 kg of TNT
50kg TNT
30kg TNT
15 kg TNT
5 kg TNT
0.1 kg/m²
1
10
20
R I
R II
[m]

Figure 7

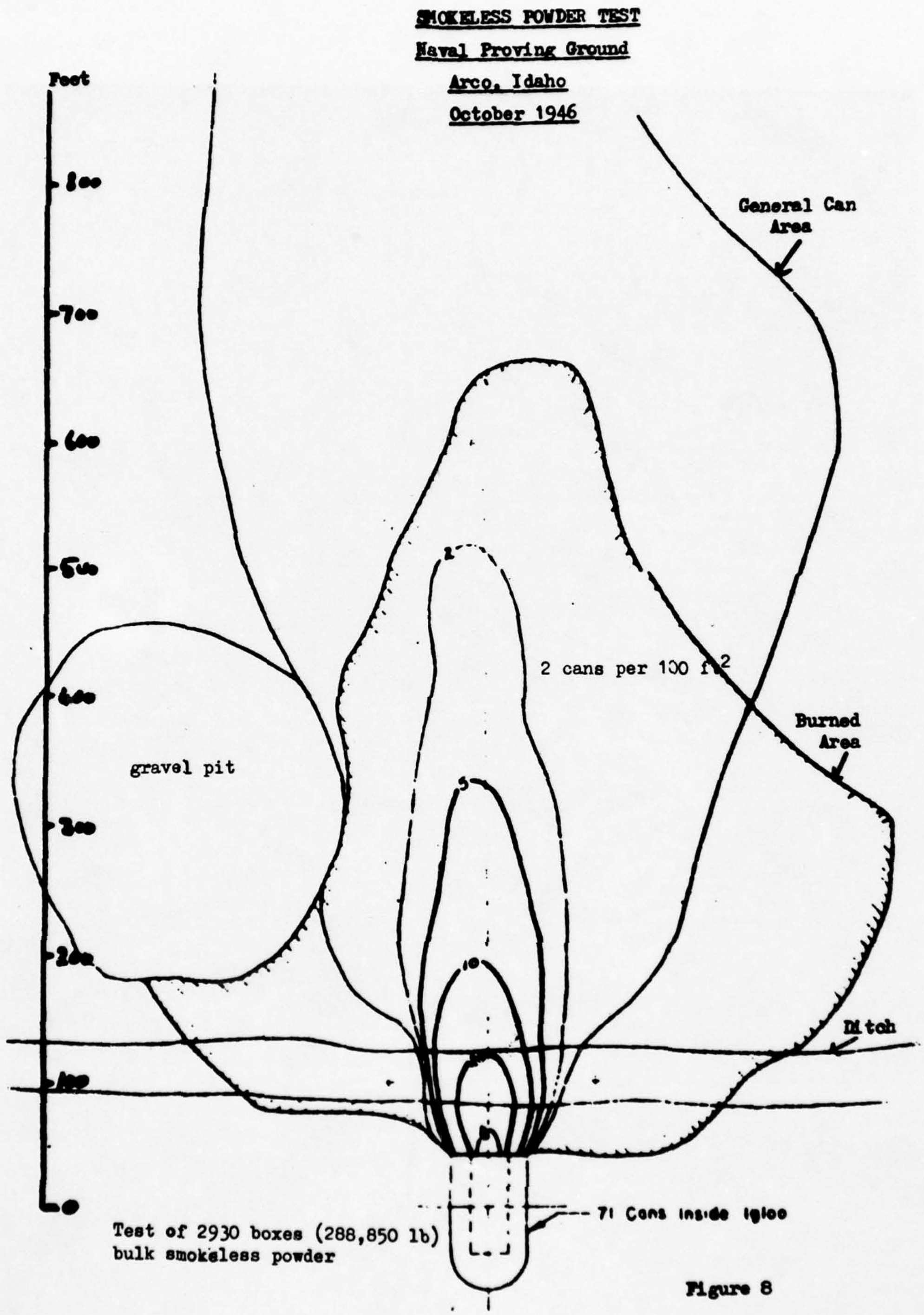

SMOKELESS POWDER TEST
Naval Proving Ground
Arco, Idaho
October 1946
Feet
800
700
600
500
400
300
200
100
0
General Can Area
2 cans per 100 ft²
Burned Area
gravel pit
Ditch
71 Cans inside igloo
Test of 2930 boxes (288,850 lb) bulk smokeless powder

Figure 8

Typical Arrangement of Stack of Bulk Propellant for Ignition Trials

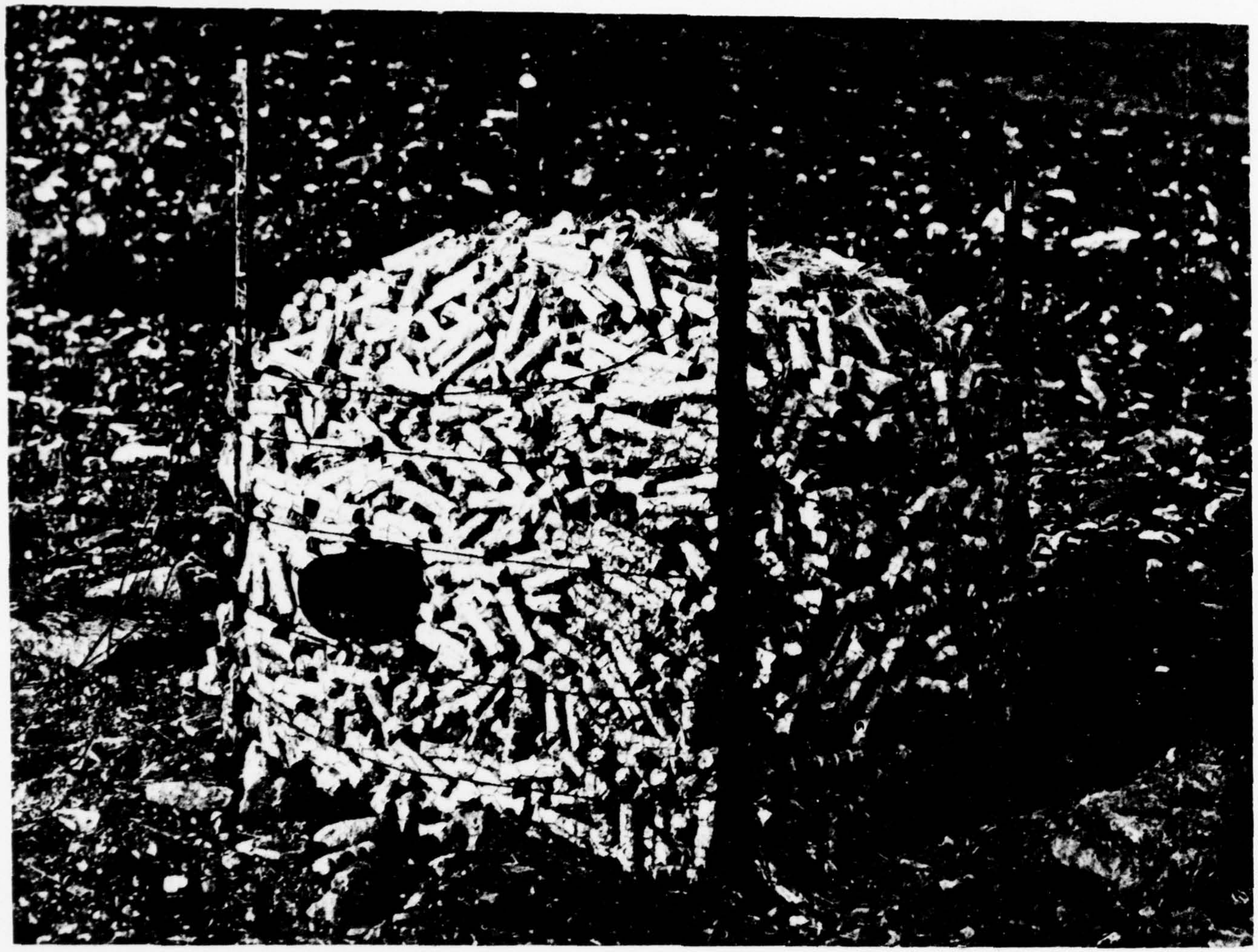


Figure 9

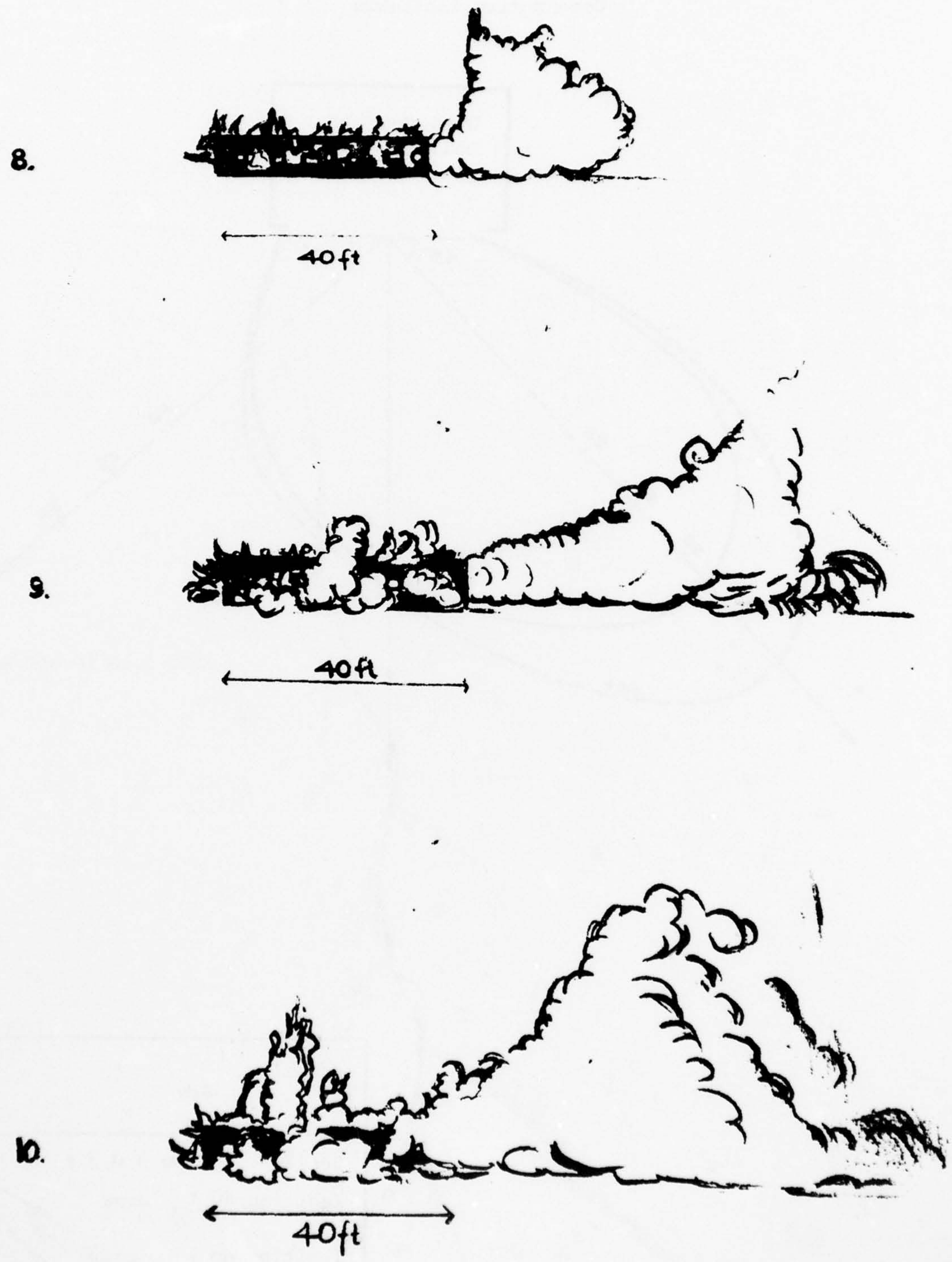


Figure 10. Sketches showing jets of flame from building

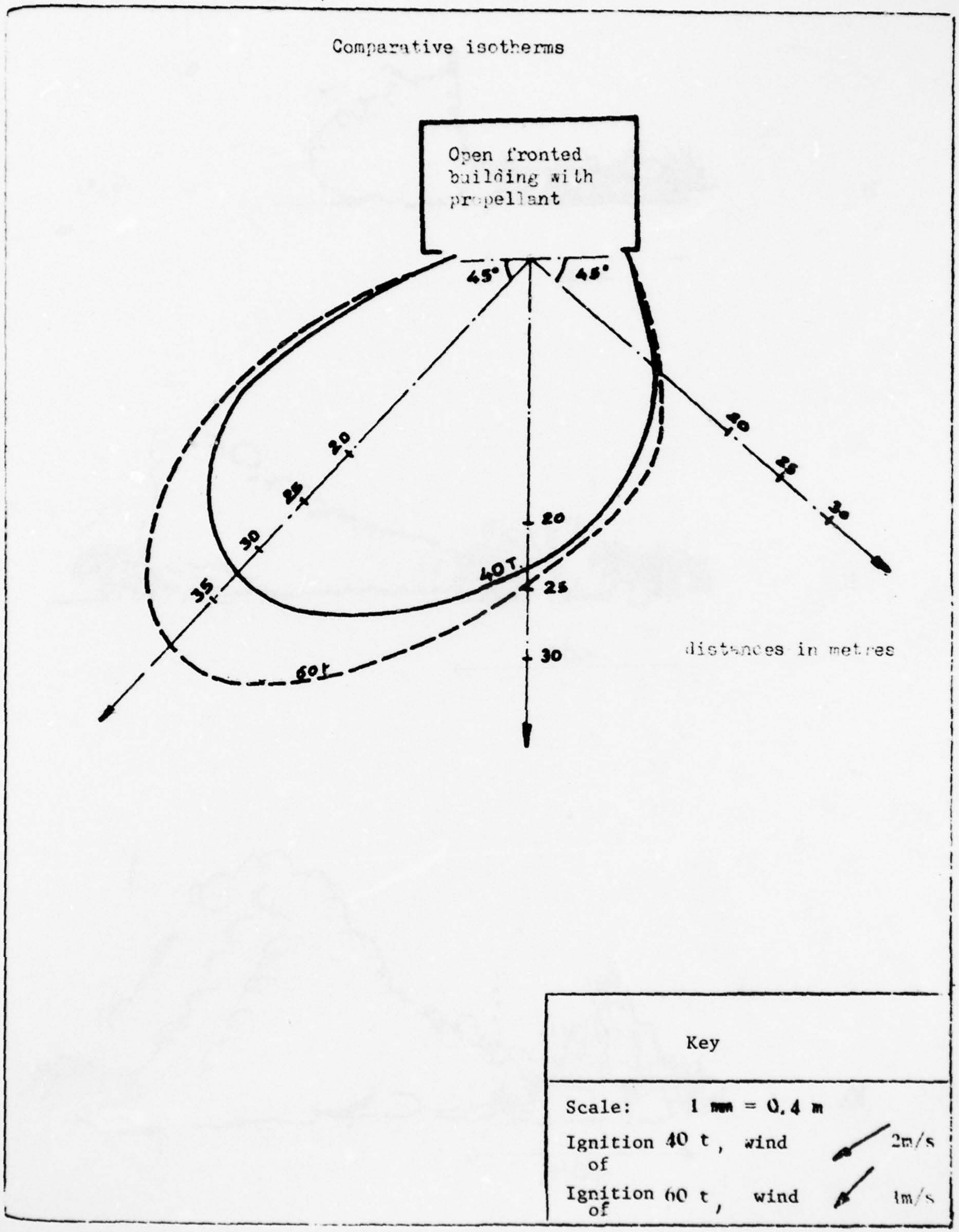

Comparative isotherms
Open fronted building with propellant
45°
45°
20
25
30
35
40T
60t
20
25
30
distances in metres
Key
Scale: 1 mm = 0.4 m
Ignition of 40 t, wind 2m/s
Ignition of 60 t, wind

Figure 11

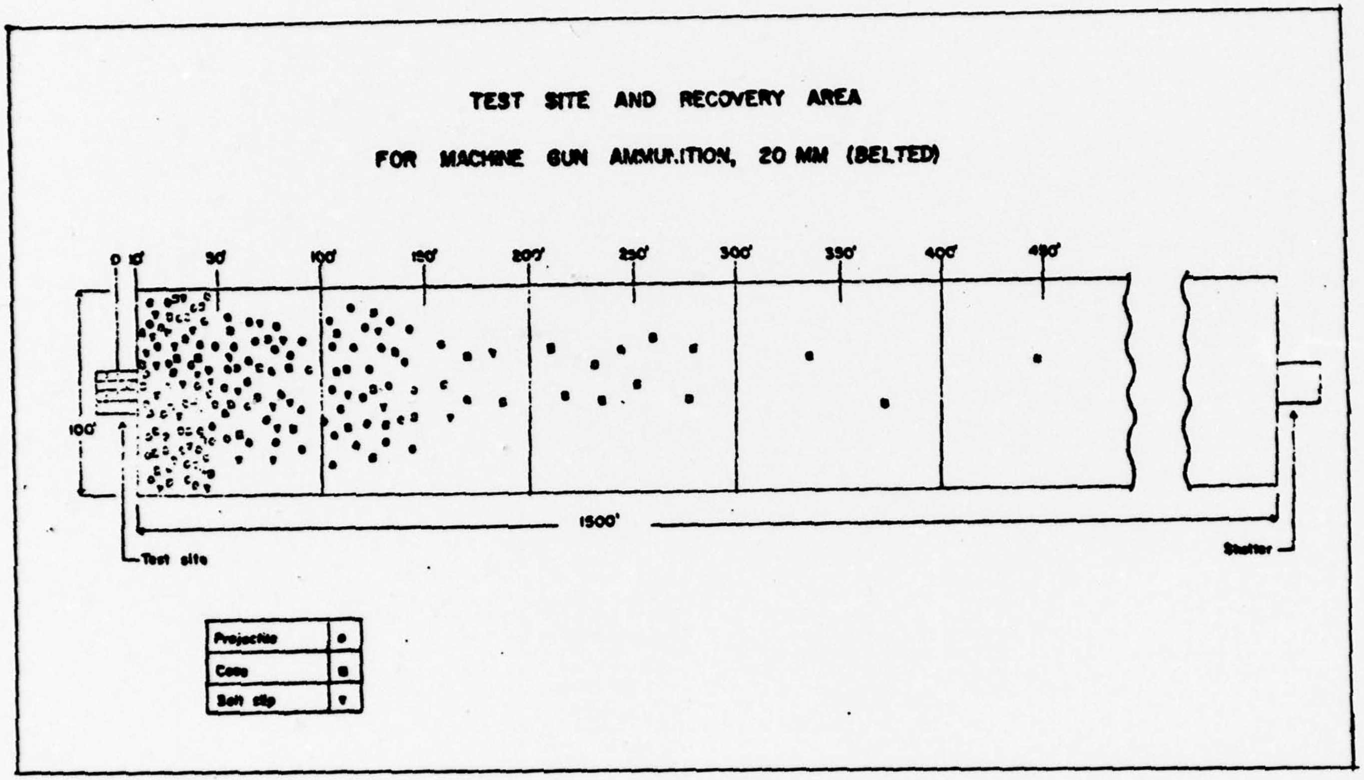

TEST SITE AND RECOVERY AREA
FOR MACHINE GUN AMMUNITION, 20 MM (BELTED)
0
10'
30'
100'
150'
200'
250'
300'
350'
400'
450'
100'
1500'
Test site
Shelter
Projectile
Case
Belt slip

Figure 12

IGNITION AND COMBUSTION CHARACTERISTICS OF WATER-GEL EXPLOSIVES

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This paper presents some data on the combustion and ignition characteristics of a few model water-gel explosives. These explosives possess a common characteristic of having minimum burning pressures (MBP) very much higher than atmospheric pressure. The MBP depends strongly on the water content in the composition. At a typical water content of about 10 percent, the MBP is found to be about 48 and 293 atm. for systems sensitized by ethylene glycol mononitrate (EGMN) and containing no explosive sensitizer, respectively. The addition of a few percent of aluminum powder lowers these MBP's by more than a half. Above the MBP, most explosives show two distinct regimes of pressure dependence of the burn rate. The pressure exponent b of burn-rate ($u = ap^b$) has a value near unity at high pressure and a value of 1.5 to 2.3 at lower pressure. The ignition characteristics of explosive-sensitized water-gel explosives is investigated above the MBP. Results are analyzed using a condensed phase thermal ignition model. Kinetic parameters thus obtained are used with the theory to predict the temperature, time and energy of ignition with excellent agreement with experimental data. The activation energy is found to be about 34.5 Kcal/mole for these EGMN sensitized compositions.

This work is supported by the Canadian National Research Council under the Industrial Research Assistance Program.

INTRODUCTION

In the manufacturing and handling processes of explosives where shock waves are generally not generated, an explosive event, whether explosion or detonation, is built up through the following sequence of events: 1. process events, 2. initiation or ignition, 3. sustained combustion and 4. explosion or detonation. Therefore any realistic quantitative process of hazard assessment and predictions (such as the one presently used at the Canadian Industries Limited) must be based on a good understanding of the ignition and combustion characteristics of the particular explosives concerned.

The recently developed class of water-gel explosives has presented perplexing problems in their hazard quantification largely because of their negative response to conventional hazard testing techniques (e.g. drop hammer, friction, etc.). Recent experiments showed that the apparent insensitiveness of these water-gel explosives was due to their low ignitibility and combustibility at or near standard atmospheric pressures. This paper presents some of the results on the ignition and combustion characteristics of a few representative water-gel explosives obtained at elevated pressures (up to 400 atmospheres).

Commercial water-gel explosives can be represented by two groups: (a) NCN explosives,i.e. compositions of ammonium nitrate (AN) and other non-explosive materials and (b) explosive sensitized compositions, i.e. those containing AN and a self-explosive compound such as TNT, ethanolamine nitrate, ethylene glycol mononitrate (EGMN), etc. Aluminum is a common additive to increase the sensitivity and chemical energy of the explosive. The present study concerns mainly with an EGMN based water-gel explosive and the effect of aluminum. A few NCN compositions were also investigated, although in less detail.

EXPERIMENT

All tests were carried out with the explosive sample placed in a high pressure vessel (2 litres capacity) pressurized with nitrogen to the desired initial pressure. The pressure increase from the burning explosive was monitored by a strain-gage type pressure transducer. Initial temperature of the explosive samples was about 25°C.

In the combustion tests, the explosive was contained in a 15 cm long glass tube 1 cm. inside diameter with 1 mm wall thickness. Ignition of the explosive was done by a coil of resistance wire (0.18 ohm/cm nichrome) heated by electrical current from a 20 volt power supply. The burn-rate was determined by one or more of the following methods: signals from the pressure gauge or from a continuous ionization probe embedded in the explosive or from a few photo detectors placed at known distances along the side of the explosive charge. The continuous ionization probe was made of an insulated resistance wire wound around a small (no. 4-40 UNC) threaded brass rod. The electrical voltage created by the passage of a constant current is thus proportional to the length of the probe. Progressive shorting of the probe by the high temperature flame front reduced the voltage giving a means of monitoring the burning velocity. However, in many instances the continuous ionization probe was found to influence the burning rate due to physical or chemical effects. Therefore most of the present results were obtained by the other two techniques.

An electrically heated hot-wire ignition technique (Refs. 1-3) was used in the ignition tests. This technique was chosen because of its obvious convenience for use in a high pressure vessel as well as its advantage of having well known boundary conditions and controlability of the heat flux. The mathematical solution of the heating of an inert solid by a constant power hot wire has been obtained by Jaeger (4) providing the basis of a theoretical solution to the thermal ignition problem.

The experimental set up for the thermal ignition tests is shown in Fig. 1. The explosive sample was contained in the same glass tubes used in the combustion tests. A resistance wire was mounted on the axis of the explosive column. It was made of a 3520 nickel chromium wire* 0.051 cm diameter 10 cm long with the ends soldered onto two 0.32 cm diameter copper conductors. The resistance wire formed one arm of a Wheatstone bridge in series with a 400 watts 0.255 ohm resistor (R_1). The latter was immersed in oil to minimize heating.

Electrical current to the bridge was supplied by a constant current unit which supplied a low monitoring current (less than 0.5 Amp) continuously until a signal was sent in from the time-pulse generator which switched on a pulse of constant high current (up to 30 amp). The duration of the high current was determined by the length of the switching timing pulse which could be varied from 50 msec to 50 sec.

The Wheatstone bridge signal was amplified by dual gain amplifier having two gain settings. It normally stayed at high gain to amplify the low current signal and was switched to the low gain position throughout the duration of the high current pulse. Signals from the low and high current could be balanced with proper setting of the two amplifier gains. This combination of high and low currents allowed the wire temperature to be monitored continuously even after the high (heating) current was switched off. Because the output voltage was caused by a change in the wire resistance due to electrical heating, calibration of wire resistance against temperature thus allowed one to determine the wire temperature from the voltage. This calibration was carried out up to 800°C in a muffle furnace against a Chromel-Alumel thermocouple placed near the wire. Overall accuracy of the elctrical system was estimated to be 7°C ($\sim \pm$ 2.5%) within the temperature range of interest here.

RESULTS AND DISCUSSIONS

a. Combustion of Water-gel Explosives

The experimental minimum burning pressures (MBP) are shown in Table 1 for the various compositions investigated. While there is no theory which satisfactorily explains and predicts the MBP, its existence, particularly in the case of ammonium nitrate based aqueous explosives, is likely due to the presence of endothermic surface processes of water vaporization and the sublimation and dissociation of ammonium nitrate. It can therefore be expected that the value of the MBP will depend on the content of water as well as the heat flux from the reaction zone which is a function of the heat of reaction.

* Manufactured by Molecu Wire Corp., Norristown, Pennsylvania

The above argument is well illustrated by the experimental data (Table 1). In the case of NCN slurry, the MBP is very high (293 atm) while a similar but non-aqueous composition of ammonium nitrate/fuel oil (ANFO) has a MBP of just below 68 atm. Addition of aluminum results in a considerable lowering of the MBP. The effect is much stronger with a pigment grade of aluminum (paint-fine aluminum - mean particle thickness about 0.2 micron) than with fuel grade aluminum (mean particle size 210 micron). This is presumably due to the increased heat of reaction from the combustion of the aluminum.

A similar strong effect of water is also observed in the EGMN systems. When its content is reduced from 20% to 9% the MBP decreases from 95 atm to 48 atm, even when the content of the highly reactive EGMN decreases. The endothermic process of water vaporization evidently dominates the exothermic EGMN combustion process. Addition of aluminum again lowers the MBP. The stronger effect of paint-fine aluminum than the fuel grade aluminum is also observed here.

The burning rates at pressures up to 400 atm are presented in Figs. 2 and 3. The results are summarized in Table 2 in terms of the parameters a and b of the equation

$$u = ap^b \qquad (1)$$

where u is the linear burn-rate (cm/sec) and p is the pressure (atm).

The effect of water content on the burn-rate of the EGMN system is shown in Fig. 2. The burn-rate increases significantly with a decrease of the water content from 20% to 9%, particularly at pressures between 50 to 200 atm. The burn-rate lines in Fig. 2 show a sharp break with two distinct values of the pressure exponent b for the low and high pressure regions. The exponent b in the high pressure region (above 170-200 atm) has a value close to unity, while that for the low pressure region has a much higher value of 1.6 - 1.8.

Aluminum has an effect entirely different from water. Besides lowering the MBP, it seems to influence the nature of the combustion as shown in Fig. 3. The pressure dependency of the burn-rate for both the EGMN and the NCN systems are changed significantly with the addition of aluminum. For example, in the case of the EX-B composition, the addition of paint-fine aluminum reduces the dual pressure exponents of the burn-rate to a single value of $b \sim 1.08$ for the entire range of pressure investigated (20-340 atm). The absolute values of the burn-rate are also affected by the aluminum. In general it is observed that the burn-rate is reduced in the EX-B composition but is increased in the NCN system.

b. <u>Ignition of Water-gel Explosives</u>

A typical resistance wire heating curve is shown in Fig. 4. A sudden break in the slope of the heating curve is taken as the point of ignition giving the temperature and time of ignition. Most of the experiments were carried out in this "superheated" regime (3) where the heating current was switched off after the point of ignition. The energy flux per unit wire surface area is simply $Q_o = I^2 \frac{R'}{\Pi \ell d}$, where I is the supplied current, R' is the wire resistance, ℓ and d are the wire length and diameter respectively. The net energy flux into the

explosive is:

$$q_e = q_o - (\rho c)_w \frac{d}{4} \frac{dT_w}{dt} \tag{2}$$

where $(\rho c)_w$ is the volumetric specific heat of the wire and T_w is the instantaneous wire temperature. The total energy of ignition is then given by

$$E_{ig} = \int_o^{t_{ig}} q_e \, dt = E_o - E_w \tag{3}$$

where $$E_o = I^2 \int_o^{t_{ig}} R' \, dt \tag{3a}$$

$$E_w = (\rho c)_w \frac{d}{4} (T_{ig} - T_o) \tag{3b}$$

where E_o is the total ohmic energy supplied to the wire and E_w is the residual wire energy.

Two basic systems were investigated including the EGMN liquor and the EX-B. The former is a liquid and is therefore a homogeneous system. The latter is a representative explosive sensitized water-gel explosive containing both liquid and solids, which are AN grains with average size less than 150 μm In order to reduce the effects of convection it was necessary to thicken the explosives before testing using 3 percent guar for the EGMN liquor and 0.2 percent guar for the EX-B. A small amount of crosslinking agent was used to crosslink the explosives. The effect of aluminum was studied by the addition of 5 and 10 percent to the EX B composition. The alumnium had particle size of 50 μm or less. All experiments were carried out at initial pressures between 100-136 atm, well above the minimum burning pressure.

A thermal ignition criterion proposed by Averson et. al. (5) suggested that the ignition temperature is related to the heat flux by the following relation:

$$\frac{q_e^2}{T_{ig}^2} = \lambda QZ \frac{R}{E} \exp\left(-\frac{E}{R\,T_{ig}}\right) \tag{4}$$

where λ, Q, Z, E and R are the explosive thermal conductivity, volumetric heat of reaction, frequency factor, activation energy and the universal gas constant respectively. Relation (4) suggests that plotting $\log(q_e/T_{ig})$ or $\log(q_e/T_{ig}\sqrt{\lambda})$ versus $1/T_{ig}$ should give the effective activation energy E and QZ factor from the slope and the intercept of the straight line.

The experimental data are plotted in Fig. 5 in $\log(q_e/T_{ig}\sqrt{\lambda})$ and $1/T_{ig}$ coordinates to normalize the effect of different thermal conductivities for similar compositions. The thermal conductivity λ was determined experimentally by the transient hot wire technique (6) using the same facility at low currents (1-2 Amp). The experimental λ values are given in Table 3 together with the measured ρc values for the explosives of interest here. Each data point in Fig. 5 is an average of the results of a number of (mostly 5 to 10) separate experiments.

It can be seen in Fig. 5 that, except for the data for EX-B at low heat fluxes ($q_e/T_{ig}\sqrt{\lambda}$ < 0.3 (cal/cm^3-sec °K)$^{1/2}$), the data for each explosive can be fitted well by straight lines. A least square fit with Eq. 4 gives kinetic parameters of E = 34.6 Kcal/mole and QZ = 3.2 x 10^{17} cal/cm^3-sec for the EGMN liquor and E = 34.4 Kcal/mole and QZ = 3.25 x 10^{17} cal/cm^3-sec for the EX-B composition. These values of the activation energy agree well with experimental values for organic nitrates (7). It suggests that the ignition is largely controlled by the most active ingredient, which is the EGMN here. The larger QZ value for the EX-B reflects the higher reaction energy for this oxygen balanced composition compared to the EGMN liquor which has an oxygen balance of -25%.

From the few data available, the effect of aluminum powder seems to increase the ignition temperature for a given heat flux. This is probably due to the heat sink effect of aluminum at the threshold of ignition.

The ignition temperature of EX-B at lower heat fluxes is significantly lower than that for the homogeneous EGMN liquor. The cause of this apparently lower ignition temperature is not certain. The hot wire heating curves at low heat fluxes for this explosive exhibited a rise followed by a drop in temperature before the final exponential rise in temperature at the point of ignition. This indicates a change in the ignition mechanism due to the presence of ammonium nitrate solid grains.

The ignition time is shown as a function of $1/T_{ig}$ in Figs. 6 and 7 for the EGMN liquor and the EX-B systems respectively. Data for 102 atm. and 136 atm. in Fig. 6 show that, within the scatter of the data, pressure above the MBP does not seem to have significant effect on the ignition. The theoretical ignition time is related to the ignition temperature and the heat flux by Jaeger's (4) solution to hot wire heating problem for constant heat flux given by the relation:

$$T_{ig} = T_o + \frac{2\Pi q_o r}{\lambda} G(\alpha,\tau) \qquad (5)$$

where $$\alpha = 2\frac{(\rho c)_{explosive}}{(\rho c)_w}$$

$$\tau = \frac{\kappa t}{r^2}$$

with κ and r being the thermal diffusivity of the explosive and the radius of the wire respectively. The function G is as defined by Jaeger. The theoretical curves in Figs. 6 and 7 are derived from Eqs. (4) and (5) with the kinetic parameters obtained in the previous section. There is good agreement between theory and experiment for the EGMN liquor over the whole range of temperature investigated and over most of the temperature range for the EX-B system.

The ignition energy is shown as a function ignition time in Figs. 8 and 9. The theoretical lines were obtained using Eqs. (2-5). Agreement between theory and experiment is excellent using the activation energy and QZ factor determined above. For comparison, result by Zarko and Khlevnoi on nitroglycerine propellant is included in Fig. 8. In Fig. 9, it is seen that the

addition of aluminum increases the ignition time significantly from values predicted from theory using the respective measured thermal conductivities and the kinetic parameters obtained for EX-B. Obviously the present homogeneous model is insufficient in predicting the effects of aluminum particles which probably act as local heat sinks at the point of ignition.

CONCLUSION

The present paper presented some data on the basic characteristics of combustion and ignition of a few model water-gel explosives. All these explosives possess a common characteristic of having minimum burning pressures very much higher than normal atmospheric pressure. The MBP depends strongly on the amount of water present in the composition. At a water content of about 10 percent, which is typical for commerical water-gel explosives, the MBP is found to be about 48 and 293 atm. for explosive-sensitized (EGMN) and non-explosive sensitized systems respectively. The addition of aluminum lowers these MBP's to 20 and 136 atm. respectively for the two systems. Above the MBP most of the explosives investigated show two distinct regimes depending on the pressure. The pressure dependence of the burn rate for both regimes can be represented by the form $u = ap^b$. The exponent b at high pressures has a value close to unity. At lower pressures the value of b is between 1.5 to 2.3.

Ignition characteristics of explosive-sensitized water-gel explosives was investigated above the MBP. Results were analyzed using a condensed phase thermal ignition model. Kinetic parameters thus obtained were used with the theory to predict the temperature, time and energy of ignition with excellent agreement with experimental data. The activation energy was found to be about 34.5 Kcal/mole for the EGMN sensitized compositions investigated here which is in good agreement with literature data for nitrate esters.

In terms of the practical interest and safety, the present investigation has demonstrated the increased margin of safety of commercial water-gel explosives by the addition of water. The very high MBP's for these explosives explain the observed insensitiveness of these explosives to conventional tests at atmospheric pressure. It would also suggest that there is inherent safety in the manufacture of these explosives when they are not subjected to undue external pressures and prolonged heating at high temperature, because of their inability to sustain combustion at low pressures.

On the other hand, when external pressure is above the MBP, the explosive-sensitized (EGMN in the present case) water-gel explosives are shown to have ignition temperature and energy not too far from that of nitroglycerine propellant. Although these explosives can be ignited to sustained combustion at high pressures, the probability of a transition from deflagration to detonation would probably be low because of the large critical diameter and low shock sensitivity at high pressures and also because of the stable combustion observed. However, from the safety point of view, a sustained combustion in a high pressure container would be just as unacceptable.

In fact, because of the larger-than-unity pressure exponent b, combustion pressure would certainly build up to the more stable regime where b = 1 at pressures of a few hundred atmospheres. If the container bursts, an explosion would result forming projectiles which could readily initiate a very sensitive near-by explosive to detonation. All these point to the extreme precaution one must exercise in the design of manufacturing process involving high pressures.

Finally we must mention that the MBP's are likely to be dependent on other variables such as charge dimension, initial temperature and wall materials. These factors and the ignition of non-explosive sensitized compositions have not been dealt with here and are the logical extension of the present study in the future.

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TABLE I

Minimum Burning Pressures (MBP) for Some Model Water Gel Explosives

Explosive	Composition, weight % EGMN	H_2O	p.f. Al[a]	f.g. Al[b]	MBP (atm)
NCN [c]	-	14	-	-	293
NCN-A [c]	-	13.5	4.5	-	136
NCN-B [c]	-	13.5	-	4.5	204
ANFO [d]	-	-	-	-	68
EGMN Liquor [e]	50	20	-	-	95
EX-A [f]	21.4	16.8	-	-	68
EX-B [f]	23.3	9.3	-	-	48
EX-C [f]	16	8.9	3	-	20
EX-D [f]	16	8.9	-	3	30

a Paint-fine aluminum, thickness 0.2 micron.

b Fuel-grade aluminum, mean particle size 210 micron.

c Stoichiometric aqueous composition of ammonium nitrate, sodium nitrate, fuel oil, and aluminum when present.

d Ammonium nitrate with 6% fuel oil, 0.85 g/cm^3 density and average particle size 1.3 mm.

e Containing 50% ethylene glycol mononitrate (EGMN), 25% ammonium nitrate and water.

f Stoichiometric composition of EGMN, ammonium nitrate and aluminum when present.

TABLE 2

Burn-rates of some model water-gel explosives at 200 atm and expressed in terms of parameters a and b of the equation $u = ap^b$ (cm/sec) with p in atmospheres

Explosives	u (200 atm) cm/sec	a x 10^5 cm/sec $(atm)^b$	b	pressure range (atm)
NCN	0.53 [1]	80.0	1.14	306-408
NCN-A	0.42	7.78	1.62	136-340
NCN-B	0.19 [2]	0.084	2.33	230-408
EGMN Liquor	-	6.85	1.80	95-195
" "	0.90	450.0	1.0	195-408
EX-A	1.10	7.57	1.8	68-204
EX-A	-	550	1.0	204-340
EX-B	-	34.5	1.62	48-170
EX-B	1.5	3680	0.70	170-340
EX-C	0.96	314	1.08	20-340
EX-D	-	46	1.50	31-136
EX-D	1.2	380	1.08	136-340

1. At 300 atm.
2. Non-steady

TABLE 3

Thermal conductivity and volumetric specific heat of explosives investigated in the ignition tests

Explosive	ρc cal/cm^3 °K	λ cal/cm-sec °K
EGMN liquor	0.67	0.00104
EX-B	0.73	0.00108
EX-B + 5% Al	0.73	0.00157
EX-B + 10% Al	0.74	0.00177

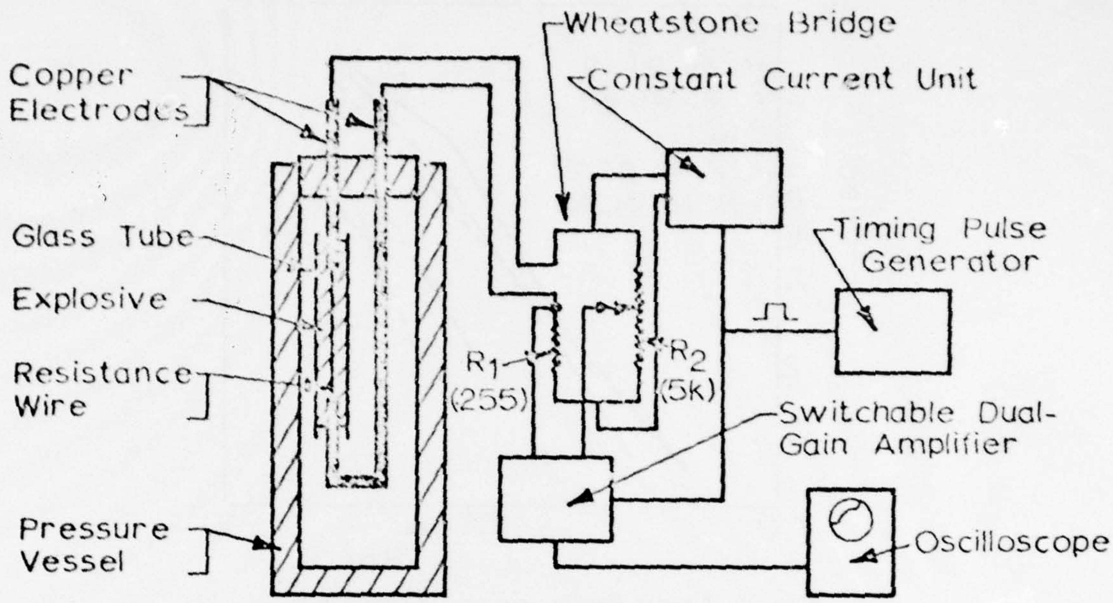


Fig.1 Schematic Diagram of the Hot-Wire Ignition Experiment Set-up

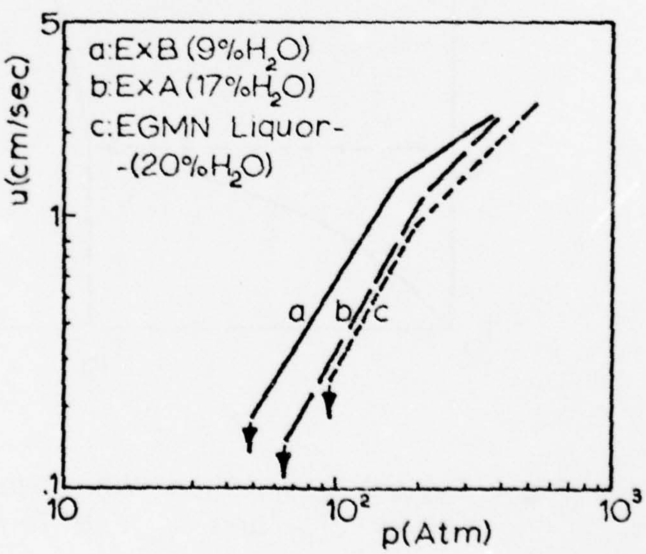


Fig.2 Burn-Rate as a Function of Pressure

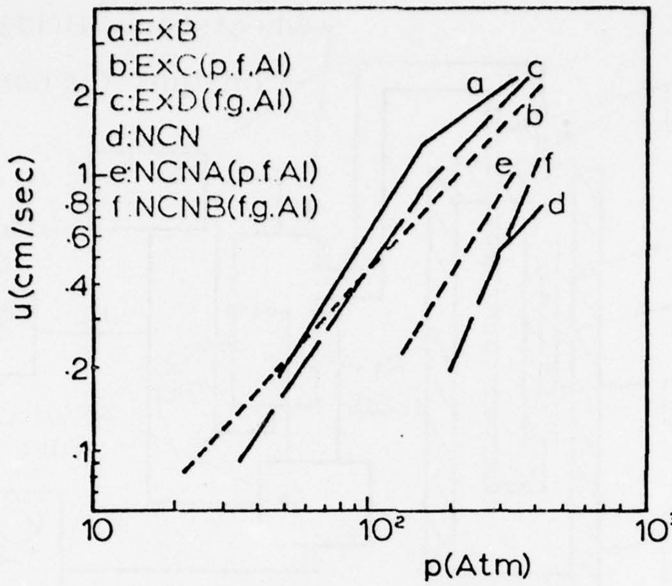


Fig. 3 Burn-Rate as a Function of Pressure

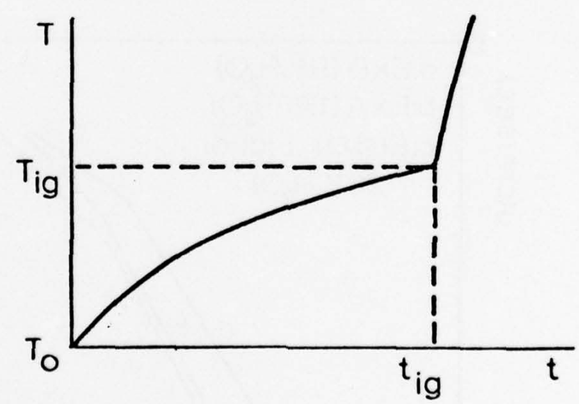


Fig.4 Typical Resistance Wire Heating Curve (T_{ig} and t_{ig} are Tempera- -ture and Time of Ignition).

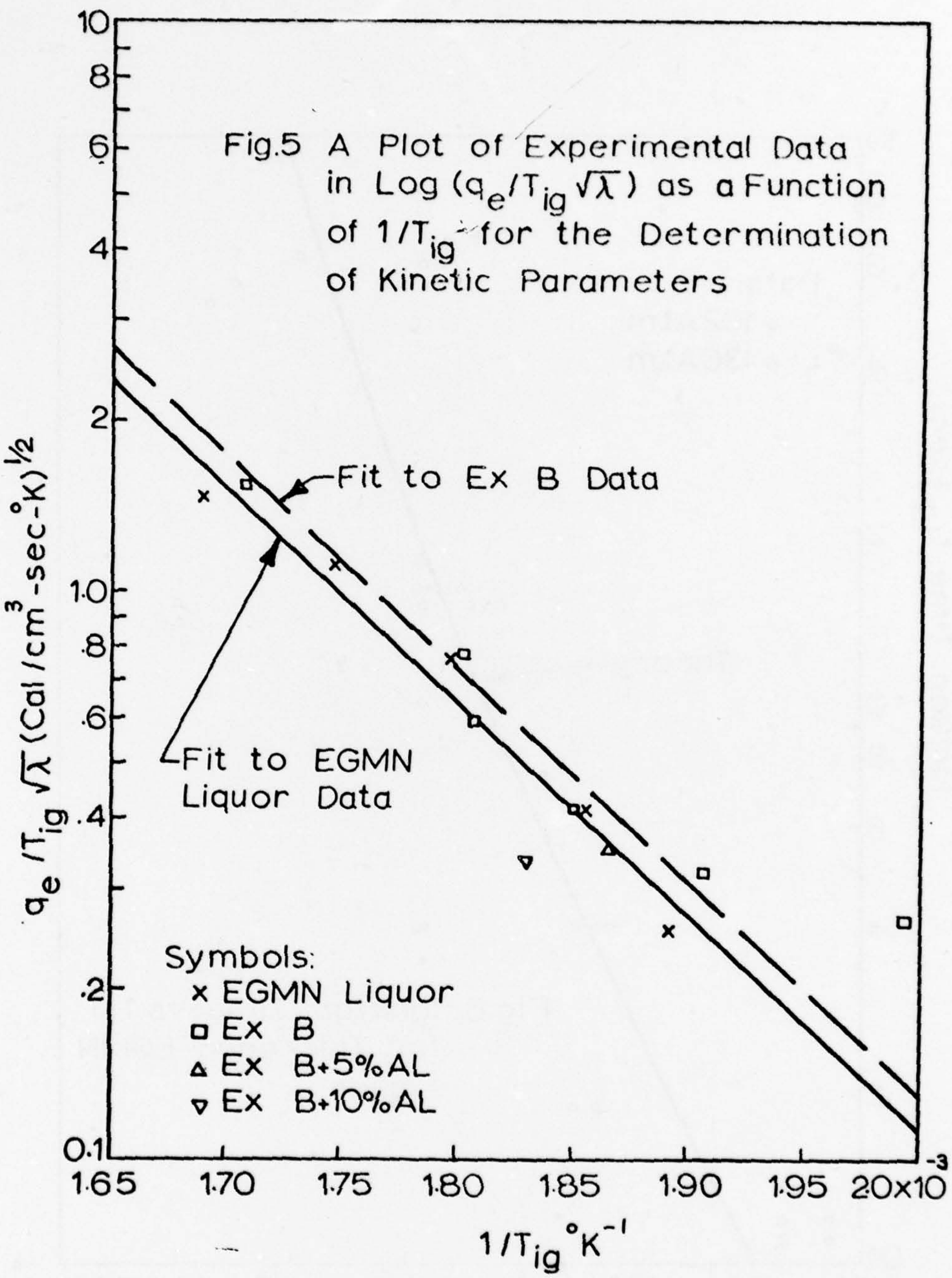


Fig.5 A Plot of Experimental Data in Log ($q_e/T_{ig}\sqrt{\lambda}$) as a Function of $1/T_{ig}$ for the Determination of Kinetic Parameters
Fit to Ex B Data
Fit to EGMN Liquor Data
Symbols:
× EGMN Liquor
□ Ex B
△ Ex B+5%AL
▽ Ex B+10%AL
$q_e/T_{ig}\sqrt{\lambda}\,(Cal/cm^3\text{-}sec\text{-}^\circ K)^{1/2}$
$1/T_{ig}\ ^\circ K^{-1}$
10
8
6
4
2
1.0
.8
.6
.4
.2
0.1
1.65
1.70
1.75
1.80
1.85
1.90
1.95
2.0×10^{-3}

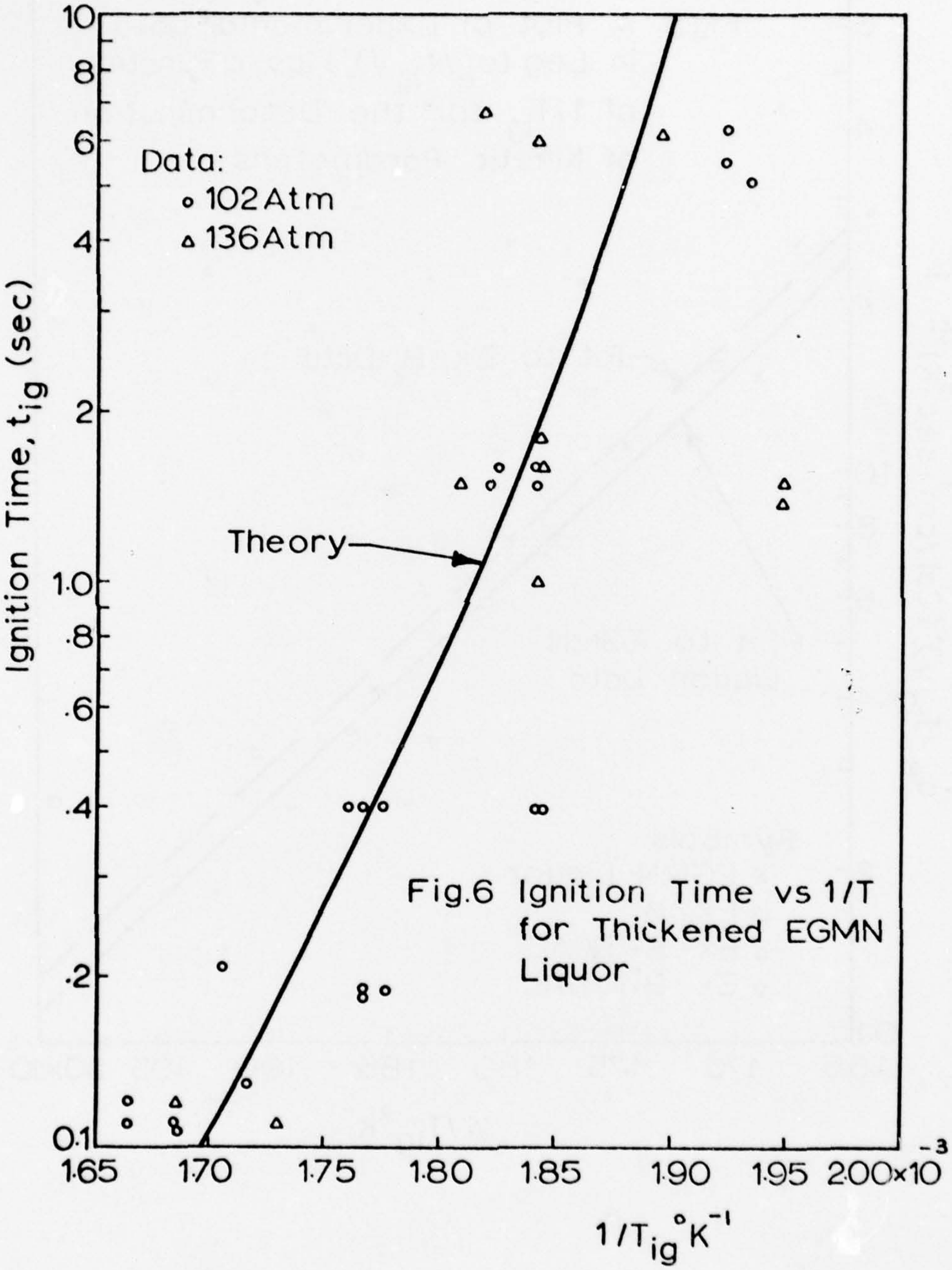


Fig.6 Ignition Time vs 1/T for Thickened EGMN Liquor

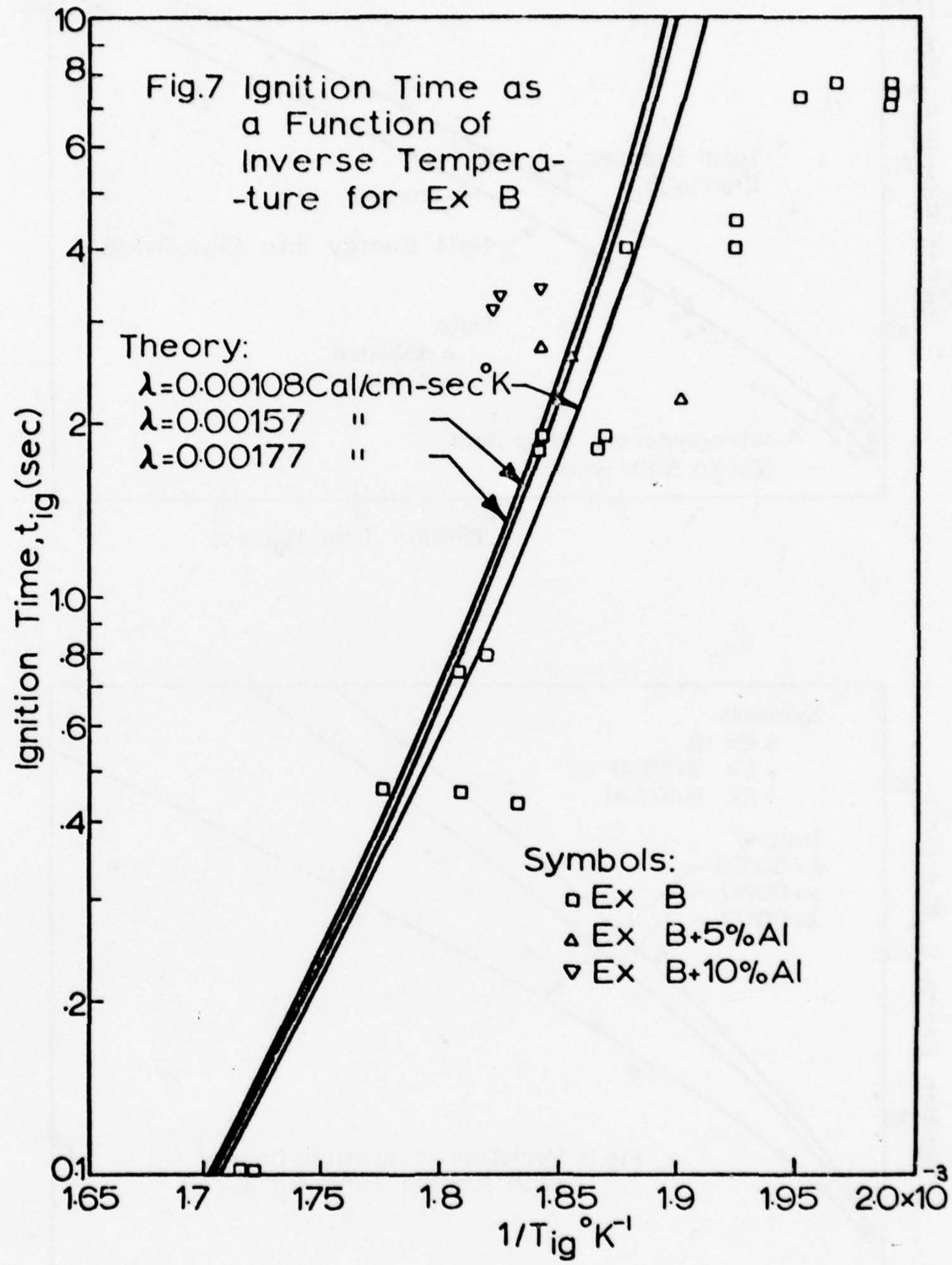


Fig.7 Ignition Time as a Function of Inverse Temperature for Ex B
Theory:
λ=0.00108Cal/cm-sec°K
λ=0.00157 "
λ=0.00177 "
Symbols:
Ex B
Ex B+5%Al
Ex B+10%Al
Ignition Time, t_ig (sec)
10
8
6
4
2
1.0
.8
.6
.4
.2
0.1
1.65
1.7
1.75
1.8
1.85
1.9
1.95
2.0×10^-3
1/T_ig °K^-1

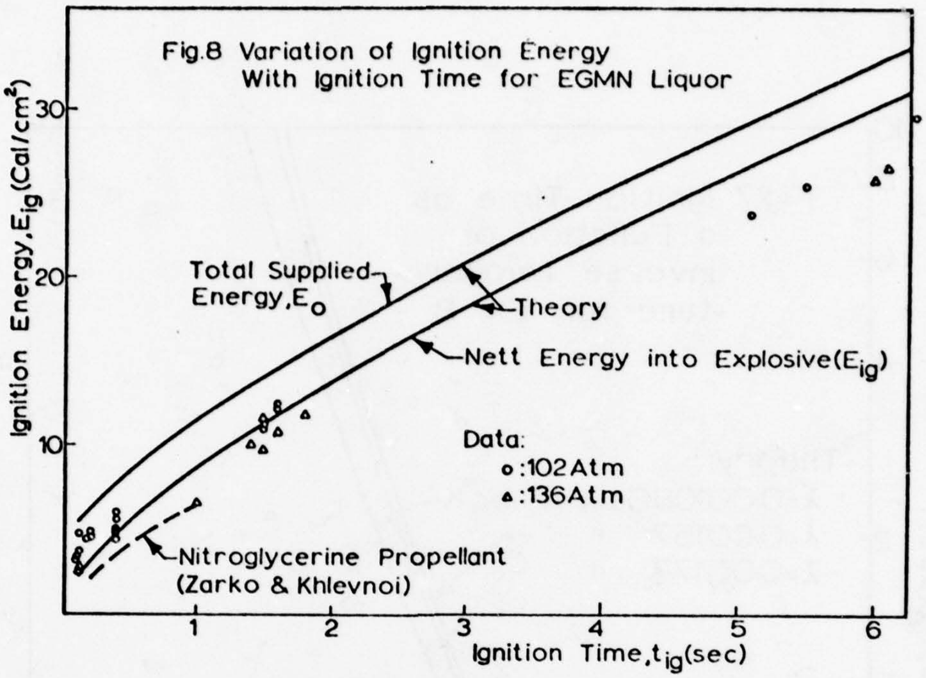
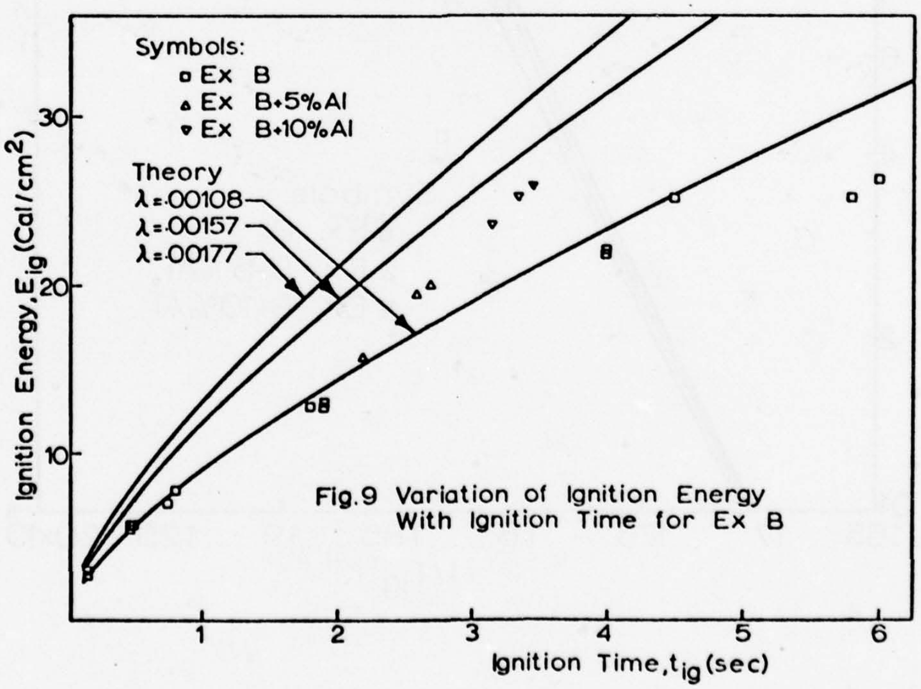


Fig.8 Variation of Ignition Energy
With Ignition Time for EGMN Liquor
Total Supplied Energy, E_o
Theory
Nett Energy into Explosive(E_{ig})
Data:
o :102 Atm
▵ :136 Atm
Nitroglycerine Propellant
(Zarko & Khlevnoi)
Ignition Energy, E_{ig} (Cal/cm^2)
Ignition Time, t_{ig} (sec)
10
20
30
1
2
3
4
5
6


Symbols:
□ Ex B
▵ Ex B+5%Al
▿ Ex B+10%Al
Theory
λ=.00108
λ=.00157
λ=.00177
Fig.9 Variation of Ignition Energy
With Ignition Time for Ex B
Ignition Energy, E_{ig} (Cal/cm^2)
Ignition Time, t_{ig} (sec)
10
20
30
1
2
3
4
5
6

STORAGE LIFE ESTIMATION OF THERMALLY AGED EXPLOSIVES

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ABSTRACT

The thermal stability of PBX(AF)-108 and Amatex-30 explosives have been investigated extensively at 30°C, 45°C, 60°C, and 75°C. A long-term storage program at elevated temperatures was undertaken to observe the behavior of these explosives under laboratory conditions of storage. Analysis of the gases evolved from various stages of the aging process was used to construct log-log plots for each storage temperature. These plots, in conjunction with other chemical and physical tests, enables one to estimate, to some degree, the storage life of the explosives under ideal conditions.

1. INTRODUCTION

Measurement of chemical stability and the prediction of safe storage life is of the utmost importance in explosives and/or munition systems. Other agencies have for many years been actively engaged in storage-life programs that employ accelerated-aging techniques. The best possible simulation of the environment is required if the future performance of an explosive is to be accurately predicted. This paper will discuss the results of an accelerated aging program aimed at predicting the storage life under a chosen environment. The method deals with simulating the aging environment of a material to establish its failure modes and, consequently, to estimate its life expectancy under ideal laboratory conditions.

A preliminary study conducted at the High Explosives Research and Development (HERD) Facility at temperatures of 60°C, 80°C, and 120°C showed substantial gas evolution. The study was run in a helium (760mm) atmosphere under controlled environment to study the new concept and to pinpoint weak areas in the accelerated-aging concept. It was determined that the temperatures were too high to give realistic "aging" results which could be correlated to ambient conditions.

2. OBJECTIVES

To investigate the ability of PBX(AF)-108* and Amatex-30 explosives to survive long-term storage under controlled laboratory conditions.

To study the degree of sample degradation by both chemical and physical means and to correlate this degradation with the gas evolution.

To estimate the safe storage life for these explosive systems over extended periods of time.

3. CONCEPTS

Accelerated aging techniques are based on the assumptions that (1) all materials react either with their environment or with themselves, (2) these reactions are continuous at all temperatures so that materials are constantly degrading with age, and (3) these reactions are normally accelerated under conditions of elevated temperature.

Various workers refer to using activation energies to predict long-term storage life. However, this study has shown that the reaction mechanisms of the explosive formulations of interest are too complex to apply the Arrhenius Equation. Therefore, the decomposition of the explosives was studied by monitoring the total gases which were evolved during accelerated aging in a closed system of a constant volume, as a function of time at each respective temperature.

The concept of the study was based on the theoretical model as shown in Figure 1. This model is based upon continuous gas evolution as a function of time at each respective temperature. Assuming that the reactions are occurring continuously,

*A plastic-bonded explosive, developed at AFATL (HERD), Eglin AFB, FL.

the decomposition of the system is monitored by periodic withdrawal of samples which have been maintained at selected elevated temperature. The degradation of the system results in excessive gas evolution in conjunction with chemical and physical changes. These provide a means for estimation of the maximum expected service life and help to identify any potential weaknesses in the explosive systems. The extent of decomposition is evaluated using the following criteria:

- Visual observations of each sample
- Density change
- Amount of weight loss
- Detonation rate change
- Total gases evolved/50 gram sample

4. INSTRUMENTATION

A cryogenic gas chromatograph utilizing dual columns, a thermal conductivity detector, and a disc integrator were used to acquire the necessary gas data. Calibration of the integrator was accomplished by injection of a known volume (0.499cc) of each standard gas studied. Volume determinations of the gas chromatograph system, inlet system, aging containers, and container stem were accomplished by the gas laws with the aid of a calibrated absolute pressure gauge incorporated in the system.

Gas Chromatograph Parameters

Detector: 250°F @ 110 MA

Flow: 40 cc/min @ 50 psi - ultra-pure helium

Columns: Dual - Porapak-Q (100/120 mesh) - 8' x 1/4"

Column Program: -100°C for 4 minutes
Heating Rate: 8°C/min to 200°C
Hold @ 200°C for 4 minutes

4.2 SAMPLE PREPARATION

The explosive systems listed in Table I were subjected to the accelerated aging process. Both explosive systems were formulated at the AFATL/DLDE HERO Facility, Eglin AFB, Florida.

Table I

Explosive	Composition	%(Percentage)
PBX(AF)-108	RDX	82.0
	Binder	18.0
Amatex-30	RDX	30.0
	TNT	40.0
	AN*	30.0

*Ammonium Nitrate

Batches of each explosive formulation were prepared by the AFATL/HERO Explosive Processing Laboratory and cast into 400 ml beakers to approximate the 50 gram samples. The samples were trimmed and weighed to 50 ±0.1 gram. The weights were then recorded as of zero time. Duplicate samples were provided for each sampling time. Each sample was placed in a stainless steel container with a stainless steel spacer added to reduce the internal volume as shown in Figure 2. The containers were evacuated to 10^{-3} torr, flushed twice and filled with ultra-pure helium, and then sealed at 760mm pressure.

The containers were next placed in controlled ovens where temperatures of 30°C, 45°C, 60°C, and 75°C (as shown in Figure 3) were maintained.

Duplicate samples were removed at varying time intervals, at each of the respective temperatures, allowed to cool to ambient before connecting to the gas chromatograph for evacuation of the container stem to 10^{-3} torr, then sampled into the gas chromatograph system.

5. DATA COLLECTION AND REDUCTION

The following procedures were used to collect and reduce the raw data:

(a) Samples were removed from the ovens and allowed to cool to the ambient temperature for safety reasons.

(b) The aging container is coupled to the gas chromatograph via stainless steel tubing utilizing a silver/nickel alloy washer to seal the high-vacuum connection.

(c) The inlet system and absolute pressure gauge were evacuated to 10^{-3} torr.

(d) Using liquid nitrogen (N_2) the columns are cooled to -100°C before sample injection.

(e) The sample container valve is opened to allow pressure of the systems to equilibrate and the net pressure is then recorded. Then high-purity helium is used to bring the system pressure to 760mm.

(f) Appropriate valves are closed and the sample of the inlet system is directed through the gas chromatograph columns to the detector.

(g) The columns remain at -100°C for 8 minutes, then are temperature programmed at 8°C/min to 200°C and held at 200°C for additional 4 minutes to clear the columns.

(h) Each component of the gas sample is recorded on a strip chart recorder. The retention time and area are printed out by the integrator. This data is used to calculate the amount of each gas in the system.

(i) The printout of data is in arbitrary units which correspond to counts per amount of gas. A calibration of the system for each gas constant based on standard gases is shown in Table II.

(j) The amount of each gas going to the gas chromatograph and the amount in each container is then calculated as in the following:

Example: N_2

N_2(Inj System) = Integration counts x calibration constant.

$$N_2(\text{total in bomb}) = \frac{(N_2(\text{Inj sys.}))(V_{\text{system}})}{V_{(\text{Inj sys.})}}$$

$V_{(\text{system})}$ = Total volume of the system plus volume of the bomb, minus volume of the sample.

$V_{(\text{Inj})}$ = Volume of the GC inject system.

N_2 (Inj sys) = Amount of N_2 found in the injected sample.

The above is done for each gas detected in the bomb.

(k) Amount of each gas in the bomb is normalized to a 50 gram sample size and corrected to STP conditions.

(l) Log-log plots of total gases evolved *vs* time stored is constructed for each temperature studied, from the least squares analysis of the data.

(m) The test criteria described in Table III are used to set the failure point baseline of the explosive systems. Extrapolation of the curves allows one to estimate the storage life expectancy at selected temperatures.

6. DISCUSSION

The fact that compounds of the most diverse nature can affect the decomposition kinetics suggests a complicated reaction mechanism takes place in these explosive systems. The experimental data obtained in this study does not allow an unambiguous interpretation of the reaction mechanism. The initial raw data show to some degree the typical S-curves as observed for organic decomposition. The products of decomposition in both systems were nitrogen, oxygen, nitric oxide, nitrous oxide, carbon dioxide, carbon monoxide and water. The larger amount of the total gases was contributed by nitrogen and carbon dioxide in both systems. However, each explosive shall be discussed separately as follows: The onset of sample failure has been designated at level "A" on the plots. The point of complete failure of the explosive system is designated by the level "B" on the plots. These failure points were based on the chemical and physical test results of the 75°C data.

6.1 PBX(AF)-108

In the early stages of storage at the 30°C and 45°C temperatures, the data showed considerable scatter, the color of the samples was unchanged and no weight loss was noted. The 30°C data has not been plotted due to extreme scatter and loss of gases from these samples due to container leakage. After 104 weeks of storage at 60°C, the samples still appeared serviceable with only a slight discoloration and small weight loss. Appreciable weight loss (0.13g/50g) was noted at the 48 week at 75°C. The samples stored at 75°C for 64 weeks showed softening of the binder system, extreme discoloration, cracks, and a brownish-yellow liquid condensed in the container at the 80th week of storage at 75°C. At this point the explosives would have been unserviceable for a munition system.

Figure 4 represents a log-log plot of data obtained at 45°C, 60°C, and 75°C. The maximum limit of gas evolution was set at 20ml. At this point in storage time, the system began to fail, as evidenced by other chemical and physical tests (see Table III).

The raw data obtained at 75°C began to deviate from a straight line at the 80th week of accelerated aging, thus all the curves were fitted to a least squares analysis. Extrapolation of the curves allows an estimation of the storage life as follows:

PBX(AF)-108

Storage Temperature	Estimated Storage Life
75°C	1.4 years
60°C	7.1 years
45°C	>32 years

The storage predicted by this study on PBX(AF)-108 is perhaps a maximum estimation of the life expectancy of the explosive stored in a munition. Under field storage, with exposure to moisture and temperature cycling (unsealed) as might be encountered in a munition, the life could be considerably shorter.

6.2 Amatex-30

The data acquired from the Amatex-30 sample, as shown in Figure 5, is quite reproducible. The same chemical and physical tests were used for data interpretation as for the previously mentioned PBX(AF)-108 study. Visual appearance of the Amatex samples was more prominent, weight loss was greater, and larger amounts of gas were evolved than had been noted in the PBX(AF)-108 study. There was evidence that decomposition of the samples stored at 75°C and 60°C had proceeded

to the point where the Amatex was not serviceable and/or safe by the end of the test. Also as was noted with the raw data, the curves began to deviate from a straight line at the 24th week at 75°C. The deviation of the 75°C and 60°C data could be some indication of sample failure. This began to occur at the same time period as color changes and large weight losses were noted at the 24th week at 75°C and also at the 48th week at 60°C. Level "A" and "B" failures, as defined for 75°C, were observed to occur at 60°C at times very close to those where total gas evolution reached the comparable levels. Chemical and physical tests verified this decomposition. The results of the study allows an estimation of the storage life as follows:

Amatex-30

Storage Temperature	Estimated Storage Life
75°C	0.37 years
60°C	1.07 years
45°C	12.5 years
30°C	500 years

Again, it must be emphasized that these storage estimates for Amatex are made under ideal laboratory conditions. The samples were stored under a dry inert gas atmosphere at a temperature extreme. The estimations depicted by this study are the maximums at the conditions under study. It has been shown that explosives containing TNT have survived storage since World War 1, so the long life predicted for 30°C is not unreasonable.

7. CONCLUSIONS

The techniques used to study the accelerated aging of explosives proved to be feasible. Some modifications in a future system to reduce data scatter will be necessary. It is relatively easy to link some criteria established with the degradation of the explosives. It is also noted that the reaction rate for the overall aging is different. It must be remembered that the extrapolated storage life of the explosive is only a crude approximation of the actual storage life. The influence of atmospheric air, humidity, and temperature cycling may have a pronounced effect on the samples.

8. ACKNOWLEDGEMENTS

The authors acknowledge the helpful criticism and reviews by Dr M. Zimmer and Lt Col Scott of DLDE, Armament Laboratory

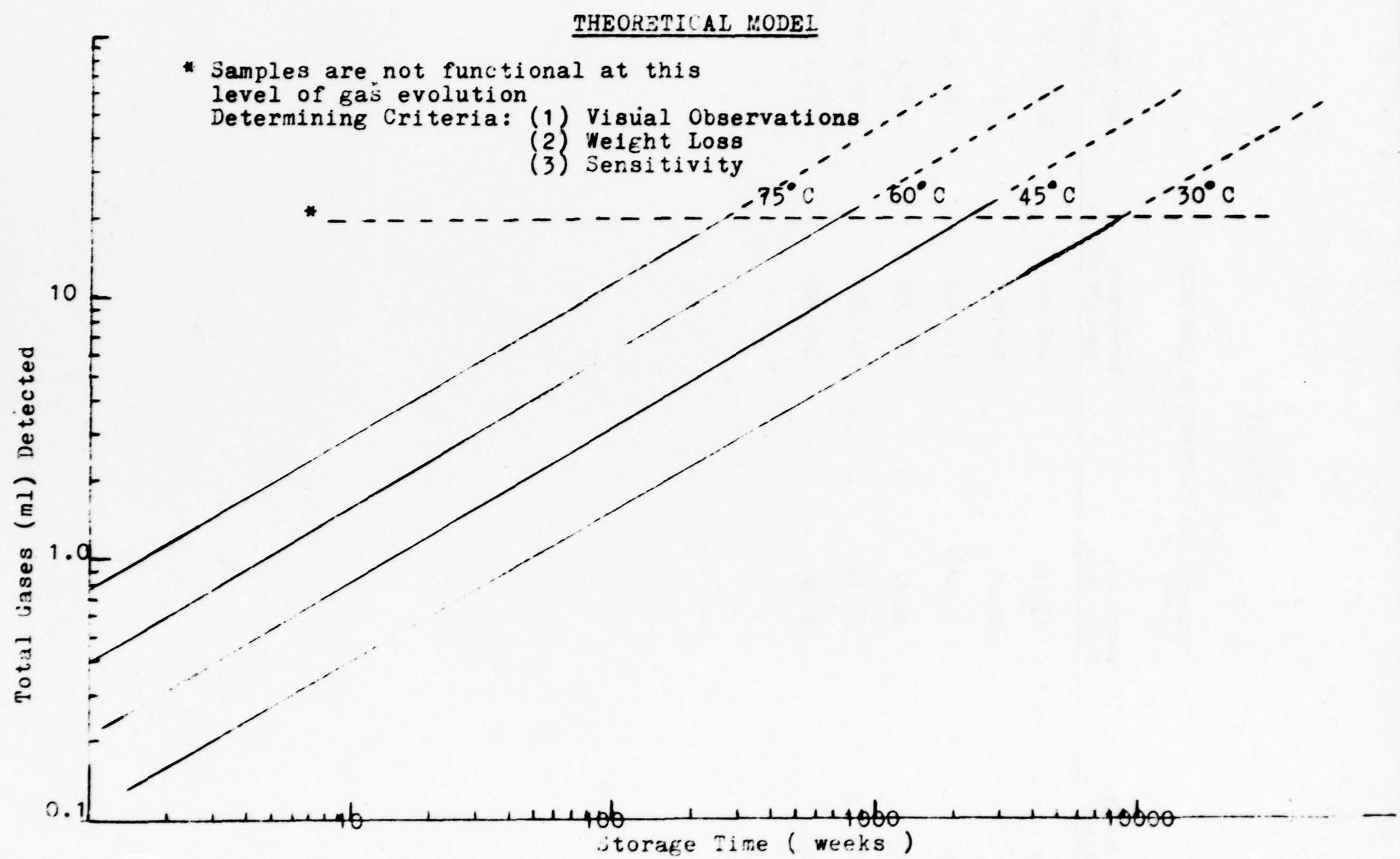

Figure 1. Total Gas Evolution vs Storage Times.

TABLE II

STANDARD GAS CALIBRATION CONSTANTS

Standard Gas (0.499(ea)	Retention Times (min)	Integrator Counts/0.499 cc	Gas Constants cc/count
N_2	13.14	165,900	3.01×10^{-6}
O_2	14.15	154,950	3.22×10^{-6}
CO	15.20	171,400	2.91×10^{-6}
CO_2	26.41	222,200	2.25×10^{-6}
NO	16.15	163,300	3.05×10^{-6}
N_2O	28.02	236,400	2.11×10^{-6}

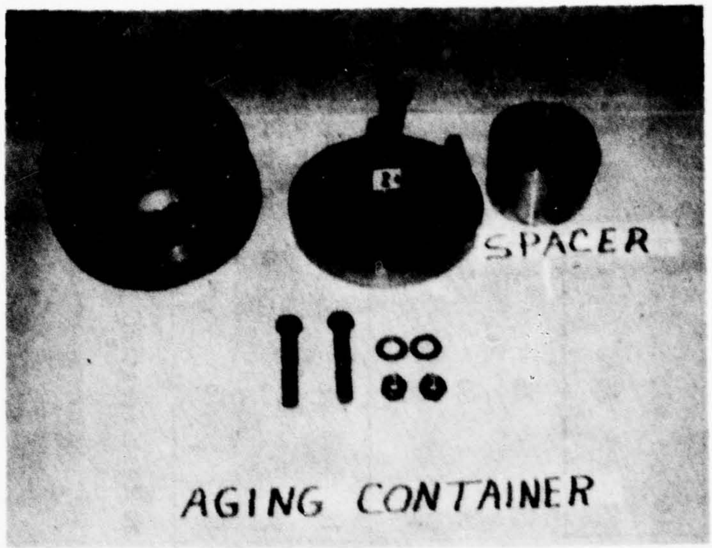

Figure 2 - Aging Container with Spacer

Figure 3 - Aging Ovens

TABLE III

ACCELERATED AGING STUDIES (RESULTS)

CRITERIA	(1) AFX-108			(2) AMATEX		
TOTAL GASES FOUND	*0.4cc	30cc		0.9cc	60cc	
	WK	T^oC	Density	WK	T^oC	Density
Density: 1. (1.58g/cc)	64	75	1.57	16	75	1.49
2. (1.63g/cc)	80	75	1.55	24	75	1.41
Wt Loss (g)/50g	104	30 + 45	N.C.	16	75	0.10
	104	60	0.01g	56	60	0.08
	48	75	0.13g	40	75	5.73
Visual	80	75	Decomposed, cracked condensate in bomb	16	75	Dark color
				24	75	Very dark - cracked
	64	75	Discolored	32	75	Melted
Detonation Rate Amb. T_o 7.836mm/ms	64	60	7.580	No test (casting problem)		
	80	60	7.818			
	96	60	7.880			
	(A)					

*Bad data scatter
(A) 75^o sticks melted

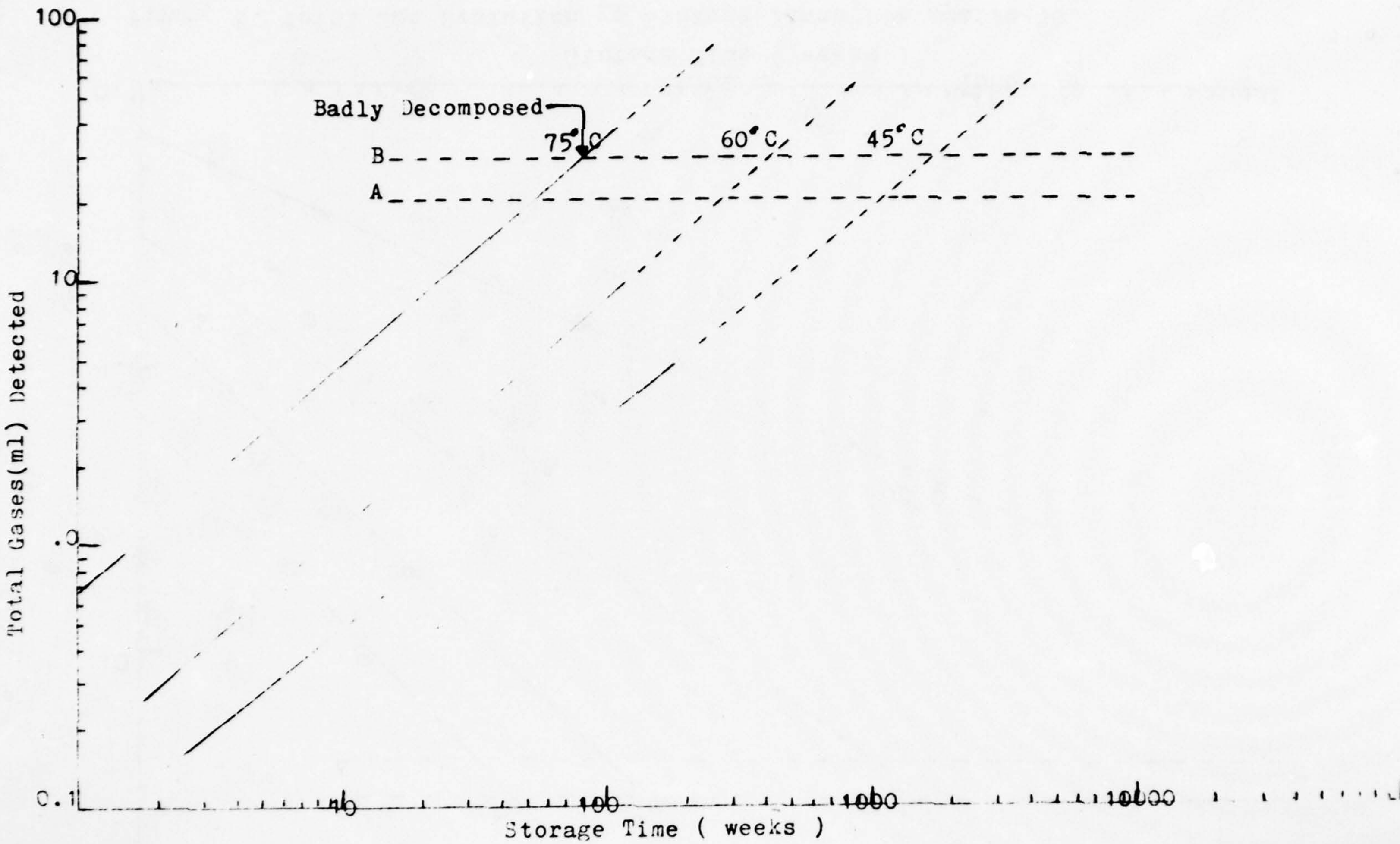

Figure 4. Total Gas Evolution vs Storage Times for PBX(AF)-108.

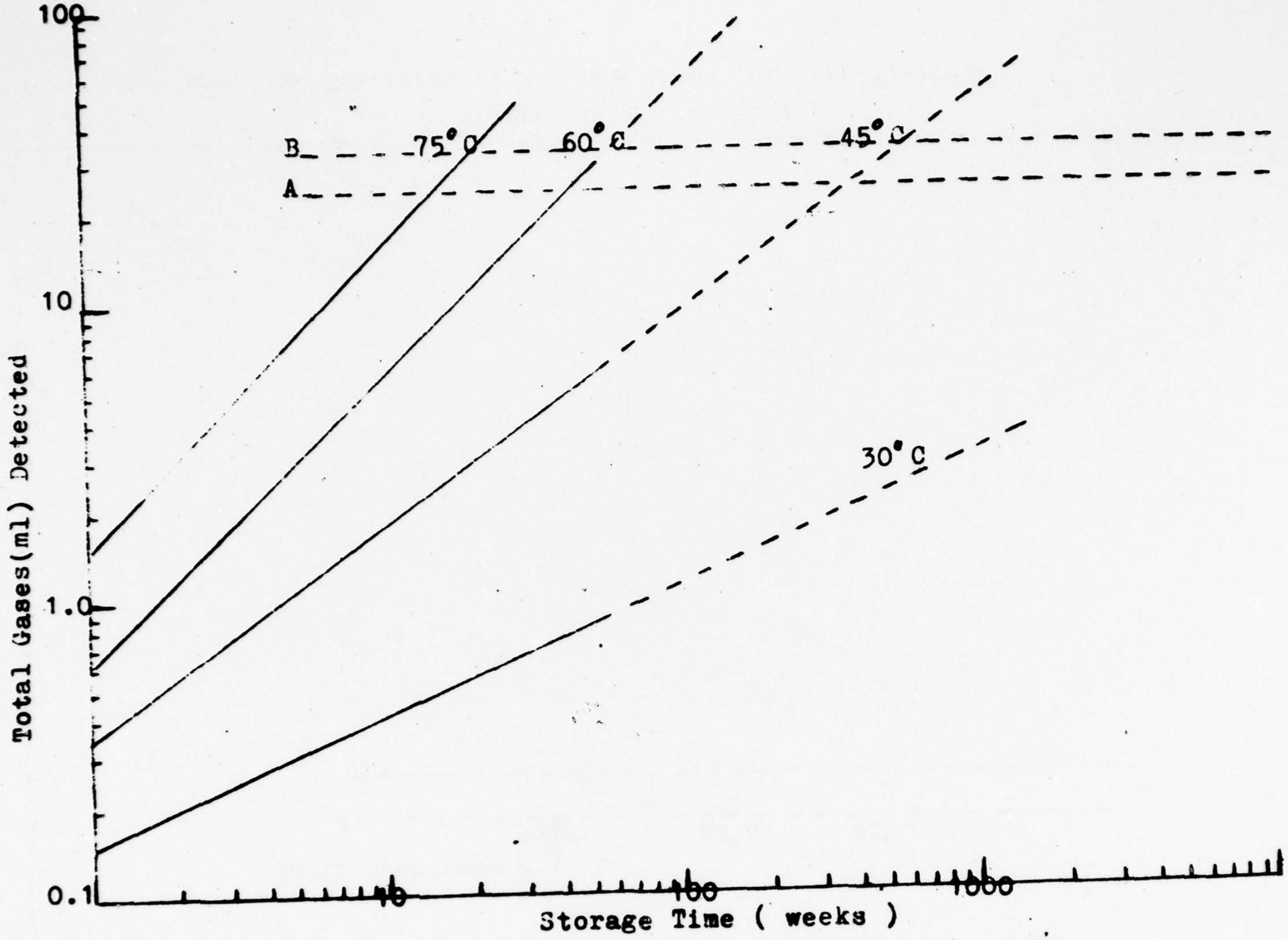

Figure 5. Total Gas Evolution vs Storage Times for Amatex-30.

NAVY EXPLOSIVES

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Explosives technology has changed dramatically in this country in the last decade. There are military explosives available today that can significantly reduce the hazards associated with the unintentional initiation of munitions by fires, hard impacts, or enemy actions. (V.G. 1) In this briefing, I will address the Navy's requirements for insensitive ordnance; talk about modern Navy explosives technology; present safety tests data on in-service Navy munitions; and finally, summarize and make recommendations.

(V.G. 2) The need for explosives that are resistant to fragment impact and that will burn rather than detonate in fuel fires was forcefully brought to our attention on 29 July 1967 and again on 14 Jan 1969 by the flight-deck fires aboard the aircraft carriers FORRESTAL and ENTERPRISE. (V.G. 3 and 4). The destructiveness of munitions cook-off reactions is demonstrated in these pictures. Not shown are the 150 or so fatalities that resulted from these two incidents.

Other incidents that dramatized the need for insensitive munitions were the 5-in and 8-in inbore prematures experienced during the South-east Asian conflict and the railroad train explosions caused by fires in boxcars at Tobar, Nevada, Roseville, California, and Benson, Arizona in the late 1960's and early 1970's.

The utility of using insensitive explosives in Navy munitions is addressed in an operational requirement (OR) document forwarded by the Commander, Naval Sea Systems Command with strong endorsement from the Chief of Naval Material to the Chief of Naval Operations in March of 1978. The operational problems addressed are: (V.G. 5) (1) unintentional initiations (2) aerodynamic heating of externally carried ordnance on high-speed aircraft; (3) problems with munitions in hot gun barrels; (4) potential vulnerability of munitions to point defense systems; and (5) reliability of munitions under extreme environmental conditions.

There has been a great deal said in recent months both in and out of the DOD about insensitive high explosives (IHE's). Some proponents of IHE's like to say that using these materials would essentially eliminate ship survivability problems or, that these so-called "wooden explosives" can reduce quantity-distance requirements for explosives materials to zero. Unfortunately I believe that this is too optimistic; however, vast improvements are possible. The table shown (V.G. 6 without overlay) lists the properties of selected explosives. Detonation velocities and densities are given because they relate to effectiveness. Gap, impact, and temperature limit data relate to safety. Temperature limit is important for explosives used in munitions exposed to aerodynamic heating. Gap sensitivitiy is the number of ten thousands of an inch plastic cards that must be interposed between a small (about 1/3 pound) donor charge and an acceptor charge of the test material to prevent detonation 50 percent of the time. Thus, the smaller the gap, the less sensitive the explosive.

Impact sensitivity refers to the height that a 2.5 kilogram steel weight must be dropped on a small sample to explode it 50% of the time. Here the larger the number, the less sensitive the material. Impact sensitivity measures the ignition characteristics of a material. Propellants, because they are fairly easy to ignite, generally have low impact sensitivity values.

Triaminotrinitrobenzene (TATB) and nitroguanidine (NQ) are the two compounds that are oftentimes referred to as "wooden explosives". These laboratory data show that they are indeed insensitive compounds. The two materials marked with an asterisk are in-service explosives shown here for comparison. Note that the top five materials are substantially less sensitive in both gap and impact sensitivity and have higher temperature limits than the two in-service explosives. Of the explosives listed, explosive D is used in Navy large caliber projectiles and diaminotrinitrobenzene (DATB), is used in the Sparrow missile warhead.

For years the Navy laboratories have been trying to make useful and affordable compositions out of TATB. TATB is a good but very expensive explosive. It is one of the most insensitive explosives known. The Naval Surface Weapons Center, White Oak, Maryland started working with TATB in about 1956; however because of the high cost (between 500 to 1000 dollars per pound) and unavailability of the material, the work that could be done was always limited. The Department of Energy became interested in TATB in the mid to late 1960's. The Los Alamos Scientific Laboratory, Los Alamos, New Mexico did substantial work to simplify the chemical synthesis. As a reuslt of the price to TATB has been reduced to between 30 dollars to 50 dollars per pound and it is projected that in million pound quantities, the cost can be reduced to 12 to 14 dollars per pound. LASL recently developed a pressed TATB formulation and the Department of Energy (DOE) is using it in nuclear weapons. This pressed composition is the only TATB formulation available today.

Nitroquanidine (NQ) looks reasonably good on paper; however, it is only about 75 percent as brisant as TNT. Also, the density shown on the table is not readily achieved. NQ has a low heat of explosion and because of this it is used quite extensively in cool-burning propellants. Its use as an explosives has not been attractive however.

In selecting explosives for use in munitions, several characteristics must be considered--safety is but one of these. (V.G. 7) effectiveness, survivability, reliability, cost, processability, and availability of materials are also important. This is why the Navy has chosen to develop plastic bonded explosives (PBX's) that, in-so-far as possible, optimize all the competing requirements. (V.G. 8) PBX's are heterogeneous mixtures of explosive fillers like RDX or HMX in polymeric binders. The binders can be tailored for casting, pressing, or in some cases, extruding the explosive. It should be noted that not all PBX's are insensitive explosives. Some are designed to optimize energy output and not sensitivity characteristics.

As I said before, the strong motivation for developing less sensitive explosives followed the 1967 and 1969 flight-deck fires on the aircraft carriers FORRESTAL and ENTERPRISE. Following these incidents, NAVSEA redirected some of the work in the explosives exploratory development programs. The specific goal was to develop explosives that would burn rather than detonate in fuel fires and not be sensitive to fragment impact.

(V.G. 6 with overlay) shown here compared with insensitve explosives shown previously, are some of the PBX's that resulted from that program redirection. These are made of relatively inexpensive and readily available materials. They are comprised generally of RDX or HMX incorporated into a rubbery binder. All of these are castable. Their projected costs are in the order of one to two dollars per pound. The new PBX's are generally very similar to rocket propellants and as such are ignited relative easily--this is reflected in the low impact sensitivities. They have good shock sensitivity however, and because they are rubbery, they behave very nicely in large-scale munitions safety tests.

I have shown, in the preceeding viewgraph, laboratory-type sensitivity tests data on insensitive PBX's. What I show here (V.G. 9) are some large-scale sensitivity tests results. In bullet impact and target impact, we have had no violent reactions with these explosives. This V.G. shows the results of 50 cal bullet impact on a new PBX confined in a steel pipe. The target impact sensitivty tests are with bombs propelled by rocket sled. Many of these test have been performed by the Air Force. In no case have there been any explosives reactions--even at speeds of 1100 to 1200 ft per second.

These data are of fast cook-off tests performed using various munitions (V.G. 10). Again, in no case does a violent reaction occur with the new PBX's. For example, the results of a fast cook-off test with PBXC-116 is a pressue rupture of the bomb case with no fragmentation. (V.G. 11) I will now show a fast action flim clip that compares the behavior of old and new explosives in various weapons. You will see, in quick succession, a series of tests. The first scene is of the April 1973 Roseville, California railroad disaster where a fire caused the successive explosion of 18 boxcars full of MK 81 bombs. The next two scenes are from NWC China Lake tests simulating the boxcar fire, first with tritonal-loaded bombs as had been in the train explosions at Roseville, then with bombs filled with an insensitive plastic bonded explosives (PBX).

The following scenes show MK 84 2000-pound bombs impacting onto a reinforced concrete wall at about 800 ft/sec. The first bomb is loaded with a conventional explosive. The next with an insensitive PBX.

The next scene demonstrates a fast cook-off test. The weapon used is a Shrike missile warhead loaded with an insensitive PBX. Finally, the last scene is of a 20MM bullet impact test of a Harm warhead loaded with an insensitive PBX.

(V.G. 12) To a limited extent we have demonstrated that insensitive PBX's burn rather than detonate in fires and are less sensitive than conventional explosives to bullet, fragment, or target impacts. What has yet to be shown is that these are less likely to detonate sympathetically.

A new Navy advanced development (Cat 6.3) program was approved in FY 1978 to exploit this new explosives technology. (V.G. 13) The objectives of the program are shown in this viewgraph.

I will now present some safety tests data on in-service munitions; however, before I get into that, here are some factors that you should consider when talking of munitions survivability and safety. (V.G. 14) Munition safety depends on the total system--explosives materials, propellants, and munition design. One explosive, for example, may be damaging in a cook-off environment when encased in a heavy-walled munition while, on the other hand, in a thin-walled munition it could behave quite mildly.

(V.G. 15) The data shown here on in-service munitions are from WR-50 tests. WR-50 lists the minimum warhead safety tests required for air, surface, and underwater launched weapons. Nine warheads are used to perform six different tests. In this table and in the following one, I omitted T&H cycling and vibration test results. Generally two of each of the tests shown here are performed. This table shows that slow cook-off is the most hazardous condition followed by fast cook-off then bullet/fragment impacts.

(V.G. 16) Here are more data that I retrieved from various files on weapons. Some of these data, I am fairly sure, overlap that presented in the previous table. The bottom two munitions give us a limited comparison of one of the older explosives compared to new insensitive PBX's. Both of these weapons are now loaded with new explosives. Though the data are limited they do agree with the laboratory-scale data and the advantages appear consistent with other findings.

I present no conclusions here. Let it suffice to say that, as shown on the previous viewgraph, slow cook-off is our most hazardous condition followed in order by fast cook-off and bullet/fragment impact.

In summary (V.G. 17), significant improvements in safety and ship survivability may be made by using insensitive explosives in munitions. Low vulnerability propellants (LOVA), though not addressed here, may someday be used to markedly improve powder magazine safety--Army programs on tank ammunition have demonstrated the advantages of using PBX-like materials as gun propellants.

One should not lose sight of the fact, however, that munitions safety and survivability require total systems consideration. Main charge explosives are only one facet of this complex problem. In some cases, changes in warhead designs may provide alternative approaches.

The Navy, I belive has unique requirements for insensitive ordnance. This should be recognized by the DOD (V.G. 18). Commonality of munitions among the Services and indeed, among Allied countries is in many cases desirable; however, this approach can introduce unnecessary hazards aboard ships.

I believe that it should be DOD policy to require that the most insensitive energetic materials available that meet operational requirements be used in munitions. This would make the use of munitions from other Services more acceptable to the Navy and go a long way toward achieving our goals of standardizing DOD munitions. Finally, since all the explosives technology I talked about here is based on an adequate supply of RDX and HMX, the need for a second source for these explosives will soon become very pressing. The DOD should support Army plans to construct a second source remote from our present facility at Holston.

In conclusion, I have tried to show examples of explosives technology available today and tried to give some idea of what could perhaps be achieved. For those of you who may be doubtful of such technological advances, keep this quotation by Henry Morton about Edison's experiments in electrical lighting in mind....."Everyone acquainted with the subject will recognize it as a conspicuous failure."

Thank you

NAVY EXPLOSIVES

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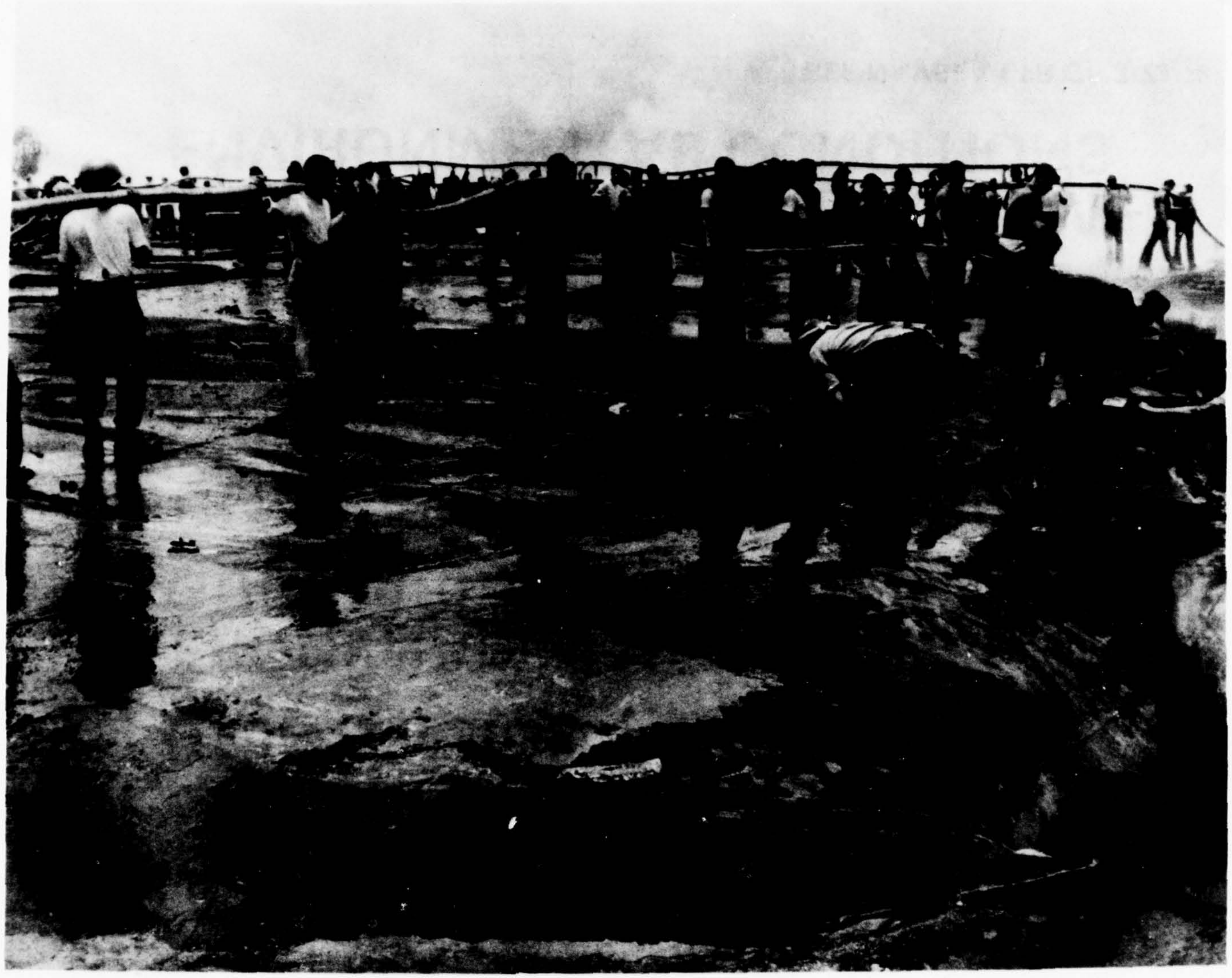
BRIEFING PRESENTS:

- NAVY REQUIREMENT FOR INSENSITIVE ORDNANCE
- NAVY EXPLOSIVES TECHNOLOGY
- NAVAL MUNITIONS SAFETY TESTS DATA
- SUMMARY/RECOMMENDATIONS

29 July 1967. Flight-deck fire aboard USS FORRESTAL (CVA-59).



USS FORRESTAL 29 July 1967. Some of the damage caused by ordnance cook-off.

OPERATIONAL REQUIREMENT
—EXPLOSIVES—

OPERATIONAL PROBLEMS

- CATASTROPHIC EXPLOSIONS FROM UNINTENTIONAL INITIATIONS
- AERODYNAMIC HEATING & HOT GUN BARRELS
- VULNERABILITY OF EXPLOSIVES TO POINT DEFENSE SYSTEMS
- INCREASED EFFECTIVENESS FOR VOLUME LIMITED MUNITIONS
- PERFORMANCE UNDER EXTREME ENVIRONMENTAL CONDITIONS

REF NAVSEA LTR OF 3/23/78

INSENSITIVE EXPLOSIVES

MATERIAL	DENSITY (gm/cc)	GAP SENSITIVITY (cards)	IMPACT SENSITIVITY (cm)	TEMP LIMIT °F	DET VEL m/sec
DATB	1.84	132	> 320	422	7720
TATB	1.94	59	> 320	550	7760
NQ	1.64	93	> 320	450	8590
EXPL. D	1.55	150	235	500	7460
PBXN-4	1.70	129	> 320	422	7200
COMP A-3*	1.60	210	80	180	8520
H-6*	1.76	197	100	140	7520
PBX(AF)-108	1.58	107	41	275	7950
PBXW-109	1.65	115	33	275	7530
PBXC-116	1.65	141	30	275	8120

* INCLUDED FOR COMPARISON ONLY

COMPETING WARHEAD DESIGN CHARACTERISTICS

- SAFETY
- EFFECTIVENESS
- SURVIVABILITY
- RELIABILITY
- COST
- PROCESSABILITY
- AVAILABILITY

PLASTIC BONDED EXPLOSIVE (PBX)

- A PBX IS A HETEROGENEOUS MIXTURE OF EXPLOSIVE FILLER AND ORGANIC POLYMER BINDER
- POLYMER BINDER MAY BE THERMOSETTING OR THERMOPLASTIC
- NOT ALL PBX'S ARE INSENSITIVE

PBX SENSITIVITY TEST RESULTS

EXPLOSIVE	TEST	WARHEAD	RESULTS
PBXC-116	50 CAL. BULLET IMPACT	CONFINED IN STEEL PIPE	30/30 NO REACTION
PBXN-106	50 CAL. BULLET IMPACT	CONFINED IN STEEL PIPE	9/12 SOME EXPLOSIVE BURNED
PBXN-106	TARGET IMPACT SENSITIVITY	MK82 BOMB	IMPACT AT 660 TO 1,180 FT/SEC REINFORCED CONCRETE 8/8 NO REACT-IONS
PBXW-107	TARGET IMPACT SENSITIVITY	MK82 BOMB	SAME AS ABOVE 4/4 NO REACTION

PBX COOK-OFF TEST RESULTS

EXPLOSIVE	WARHEAD	RESULTS
PBXW-107	MK 82 BOMB	CASE RUPTURED. NO FRAGS. ONLY PART OF EXPLOSIVE BURNED
PBXW-107	MK 82 BOMB	TAIL PLUG EJECTED. EXPLOSIVE BURNED. CASE INTACT
PBXW-106	5"/54 PROJECTILE	NOSE PLUG EJECTED. EXPLOSIVE BURNED. NO DAMAGE TO SHELL
PBXC-116	MK 81 BOMB	CASE SPLIT. EXPLOSIVE BURNED. NO FRAGS
PBXC-116	ZUNI	MILD RUPTURE. NO FRAGS

NEW INSENSITIVE PBX'S

- IT HAS BEEN DEMONSTRATED THAT:
  - PBX'S BURN MILDLY RATHER THAN DETONATE IN FIRES AND ARE LESS SENSITIVE TO BULLET/FRAGMENT/TARGET IMPACTS
- TESTS ARE NEEDED TO DEMONSTRATE THAT:
  - NEW PBX'S ARE ALSO LESS SENSITIVE TO SYMPATHETIC DETONATION

EXPLOSIVES ADVANCED DEVELOPMENT PROGRAM OBJECTIVES

- LESS HAZARDOUS EXPLOSIVES
- LOWEST PRACTICAL COST EXPLOSIVES
- HIGH PERFORMANCE EXPLOSIVES
- ADEQUATE CHARACTERIZATION OF NEW EXPLOSIVES

THIS PROGRAM IS A NECESSARY PART OF A COMPLETE, COORDINATED, AND INTEGRATED NAVY EXPLOSIVES PROGRAM.

SURVIVABILITY/SAFETY FACTORS

- **EXPLOSIVES**
  - MAIN CHARGE
  - BOOSTER
  - FUZE
- **PROPELLANTS**
  - GRAIN
  - IGNITION SYSTEM
- **MUNITION DESIGN**
  - DEGREE OF CONFINEMENT
  - THERMAL PROTECTION
  - LINERS

IMPROVED SURVIVABILITY DEPENDS ON TOTAL SYSTEM CONSIDERATION

THERE HAVE BEEN NO EXPLOSIVES HANDLING ACCIDENTS WITH IN-SERVICE MUNITIONS SINCE TORPEX WAS REPLACED AFTER WWII

PRE-1970
WR-50 TEST RESULTS

TYPE REACTION	SLOW COOK-OFF	FAST COOK-OFF	BULLET	40-FT. DROP
NO ACTION	0	0	90	229
BURNING	9	48	79	4
VIOLENT BURNING	2	7	15	0
EXPLOSION	4	3	3	2
L.O. DETONATION	2	7	35	0
H.O. DETONATION	8	5	3	0
TOTAL	25	70	225	235
% VIOLENT REACTION	64	31	25	0.9

REF: NOLTR 70-216

SAFETY TESTS DATA*

MUNITION	EXPLOSIVE	SLOW COOK-OFF	FAST COOK-OFF	BULLET IMPACT	40 FT. DROP
BULLPUP	H-6/PICRATOL	1/1	1/1	8/24	NR
WALLEYE	COMP. B	1/1	1/1	0/2	0/5
MK-82 BOMB	H-6	–	10/37	8/33	0/6
SPARROW	PBXN-4	1/2	0/2	0/2	0/3
SIDEWINDER	PBXN-3	0/2	0/3	0/2	0/3
PHOENIX	PBXN-104	0/2	1/3	–	–
ROCKEYE	75/25 OCTOL	1/1	2/2	–	0/6
HARPOON	DESTEX	2/2	0/2	0/2	0/2
MK-48 TORPEDO	PBXN-103 PBXN-105	3/3 2/2	0/2 0/2	3/3 0/2	0/3 0/2
MK-46 TORPEDO	PBXN-103	1/4	0/4	0/4	0/17
STD ARM (MK-73)	PBXN-101 PBXN-106	– 0/1	2/4 0/2	2/2 0/2	0/2 0/2
SHRIKE	PBXN-101 PBX(AF)-108	0/1 0/2	1/1 0/2**	9/10 0/2	0/5 0/2

* NO. OF VIOLENT REACTIONS/NO. OF TESTS
** TWO TESTS – FUZED WHD'S DETONATED

SUMMARY

- SIGNIFICANT IMPROVEMENTS CAN BE MADE
    - INSENSITIVE PBX'S
    - IHE'S
    - LOVA
- TOTAL SYSTEM MUST BE CONSIDERED
- WHD DESIGNS MAY PROVIDE ALTERNATIVE APPROACHES
- NAVY HAS UNIQUE REQUIREMENTS FOR INSENSITIVE ORDNANCE
- STRONG 6.3 PROGRAM REQUIRED TO MAKE INSENSITIVE EXPLOSIVES ATTRACTIVE AND AVAILABLE FOR WIDE-SCALE MUNITIONS USE

RECOMMENDATIONS

- DOD SHOULD RECOGNIZE THE UNIQUE REQUIREMENTS OF THE SERVICES FOR EXPLOSIVES
- DOD SHOULD REQUIRE THAT THE MOST INSENSITIVE ENERGETIC MATERIALS AVAILABLE THAT MEET OPERATIONAL REQUIREMENTS BE USED IN MUNITIONS
- DOD SHOULD SUPPORT ARMY PLANS TO CONSTRUCT A SECOND RDX/HMX MANUFACTURING FACILITY

CORPS OF ENGINEERS' REPERTOIRE OF
EARTH-COVERED MAGAZINE DESIGNS

by

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ABSTRACT

DOD Explosives Safety Board has approved various earth-covered arch-type magazine designs over the years. Full-size magazine designs now in use include a concrete circular arch, a steel circular arch, and a steel oval arch. In the near future, a concrete oval arch design will be available. Various factors control the designers choice of one or the other: cost, location, and configuration of stored items. The security inherent to structures of this type has become increasingly important in recent years.

CORPS OF ENGINEERS' REPERTOIRE OF EARTH-COVERED MAGAZINE DESIGNS

The title of this paper is "Corps of Engineers' Repertoire of Earth-Covered Magazine Designs." What I will cover about our "repertoire" during the next few minutes is this:

- the meaning of the term "standard design"

- what some of the standard designs look like, including a new one now on the drawing board

- the pros and cons of the various designs

- and a few comments on a subject that has been receiving more and more attention recently - magazine security.

What is meant by the term "standard design"? Basically, a "standard design," as far as an explosives storage magazine is concerned, has two identifying marks:

- an Office of the Chief of Engineers, or OCE, title block on the drawing (Fig 1). (I am only talking about Army designs.)

- and a listing in the Explosives Safety Board's Manual, DOD 5154.4S, "DOD Ammunition and Explosive Safety Standards" (Fig 2).

This information will probably never actually appear on a set of drawings out for bids on any given construction job. OCE standard designs are meant to be site-adapted, that is, tailored to the peculiarities of each particular location. For magazines, this tailoring mainly involves the foundation. The re-worked designs will probably show the name of whatever agency reworked them, but somewhere in the files, the design should be traceable to a standard design - something with an OCE title block.

The listing in DOD 5154.4S is the more important of these two identifying marks. Site plans for construction projects containing magazines are reviewed by DDESB. When these site plans state that one of the listed magazines is to be built, the detailed drawings of the magazine do not have to be submitted later. There's no need. DDESB already knows the design and its limitations. This would not be the case if magazines were designed from scratch for each project.

The advantages of a standard design are obvious, in my opinion. Design costs are saved and obtaining approval of the Explosives Safety Board is simplified. But also, the user can have confidence in the end product. He will have a structure for storing his explosives that has been designed specifically for that purpose, whose design has been tested under explosives loading (the Eskimo series of tests is an example), and that is a duplicate of proven structures built elsewhere.

Now, let's talk about the magazines themselves. All Corps of Engineers-designed magazines have certain features in common (Fig 3):

- an arch to cover the stored contents

- an earth covering to catch fragments

- concrete slab floor

- concrete rear wall

- concrete head wall and wing walls

- structural steel door

- approximately 26 feet wide with a variable length, usually 80 feet. (althouth there are smaller versions of the steel-arch type)

While all magazines have arches, not all arches are the same, and this difference in arch design is the principal way we distinguish various magazines.

The most common existing type is the concrete circular arch (Fig 4) sometimes referred to as the "standard ordnance igloo." Magazines of this configuration have been in existence since before World War II. Our current standard drawing was developed in 1951. The floor width is 26'-6" and the heigth is 12'-9". The concrete arch is six inches at its thinnest point and has two layers of reinforcing steel.

This next type is the steel circular arch (Fig 5). It was developed in the early 1960's, primarily for Air Force use at SAC bases. This type of magazine has also been called a "Wigloo" after the late George Wigger. George Wigger was the individual responsible for all the Army's present corrugated-steel magazine standard designs. It was the testing of this structure at China Lake in the 60's that resulted in the reduced inter-magazine spacings that we use today. The floor width is 25' and the height is 14'-4". The arch is 1 gage steel (that's slightly more than 1/4 inch) with 2-inch deep corrugations every 6 inches. The current drawings were prepared in 1963.

Here is a recent design, the steel oval-arch magazine (Fig 6). The oval configuration creates more usable storage volume along the sides of the magazine. The basic design was issued in 1975, although a prominent feature of that design, two longitudinal concrete thrust beams on either side of the arch, has since been deleted. These were found to be unnecessary as a result of last year's Eskimo V test. The floor width is 24'-10" and the height is 14'-5". The steel for the oval arch is identical with the steel for the circular arch.

The fourth type is the one that I said was on the drawing board. It will be known as the concrete oval arch (Fig 7). It is new only as an OCE standard design. The design was originally developed by the US Army Engineer Command in Europe in 1968 where it has been referred to as the FRELOC Magazine. OCE is not just changing the title block, but is strengthening the door and headwall as well as changing all the metric dimensions to English-unit dimensions. The floor width is 25' and the height is 14'. The arch is reinforced on both faces and the minimum arch thickness is 8 inches.

While the four I've just described constitute our current repertoire of standard designs for full-size magazines, I need to briefly mention one additional type - the concrete Stradley magazine (Fig 8). There are many of them in existence, but we discourage new construction. They are expensive to build and provide no more storage capacity and no greater degree of safety than either of the oval-arch configurations. In fact, the inside dimensions of the Stradley and the concrete oval-arch are identical. If you were standing within, you wouldn't know which one it was.

I said I would discuss the pros and cons of the various designs. In other words, selecting a design for a particular project is more than throwing darts at a dartboard. These pros and cons fall under two broad categories: cost and function.

Let's look at function first. The most obvious functional difference is the storage volume which is dictated by the shape. Here's the interior volume of an 80-foot long version of the four magazines (Fig 9):

Concrete Circular Arch	21,360 cu ft
Steel Circular Arch	23,120 cu ft
Concrete Oval Arch	25,520 cu ft
Steel Oval Arch	27,120 cu ft

This is not all usable volume, of course (Fig 10). Six foot cubic containers would leave lots of dead space in a circular steel arch, but would more efficiently utilize space in an oval arch. This difference becomes less significant when small objects are stored.

A second functional difference is door size (Fig 11):

Concrete Circular Arch	8 ft X 8 ft
Steel Circular Arch	10 ft X 10 ft
Concrete Oval Arch	8 ft X 8 ft or 10 ft X 10 ft
Steel Oval Arch	8 ft X 8 ft or 10 ft X 10 ft

There are also less obvious factors. For example, if the soil in a certain area were highly corrosive, we would probably not want to use the steel arches. Nor would we want to use them where the earth cover was likely to remain saturated with water, since the joints between sections of steel plate are susceptible to leakage. On the other hand, if we were building magazines on a site with very weak soil, we might want to avoid the concrete arch which weighs about 4500 lbs per foot of length in favor of the steel arch which weighs about 700 lbs per foot of length.

After we've made a functional decision, we are ready to look at costs. Here are estimated construction costs for an 80-foot long version of our four standard magazines (Fig 12):

Concrete Circular Arch	$147,000
Steel Circular Arch	161,000
Concrete Oval Arch	171,000
Steel Oval Arch	179,000

These are January 1979, Washington, DC costs. Costs elsewhere in the United States will vary by a few percent up or down from these figures. Costs outside the United States are a little trickier. Factors such as availability of materials and labor practices enter the picture. For example, corrugated steel plate is not readily available everywhere, and labor-intensive activities like forming concrete are not always the cost burden elsewhere that they are here.

When these costs are compared to the storage volumes, the differences are diminished. This is a simplistic comparison showing construction cost per cubic foot of volume (Fig 13):

Concrete Circular Arch	$ 6.87
Steel Circular Arch	6.95
Concrete Oval Arch	6.72
Steel Oval Arch	6.59

These figures are OK for rule-of-thumb use, but because of the great variety of usable-storage situations that might occur, they shouldn't be taken too seriously.

A subject closely related to the safety of stored explosives is the security of stored explosives. Various elements of Department of Defense have been concerned with this subject in recent years. It is the consensus of the security community that earth-covered magazines are about the best place you can put explosives you don't want stolen. This consensus is evidenced by the fact that the most recent Army regulation on security of arms, ammo, and explosives specifically calls for storage in DDESB-approved magazines, and imposes rather severe construction standards for any alternate facility if by chance magazines are not available.

Here are some of the features that make these magazines desirable from a security standpoint (Fig 14):

- The points of entry are few: The door, the louvers, and the vent. Each of these points are readily protected by intrusion-detection equipment. The newer designs minimize this problem by intentionally designing the louvers and vents to make entry impossible.

- The door can readily accommodate a high-security padlock as well as a magnetic switch for intrusion detection.

- Entry through the surfaces of the structure is time consuming. There's 12 inches of reinforced concrete, minimum, on the headwall. There's two feet of earth, minimum, on the arch plus either steel plate or concrete to penetrate after that.

- Entry takes special tools. An intruder with a spade, cutting torch, and oxygen tanks would be fairly conspicuous.

- The intruder has no hiding place while attempting entry. The crown of the arch, where the earth is most shallow, is also the point where the intruder would be most exposed.

Each of these features, by itself, is not necessarily persuasive, but when considered all together, and when integrated with lighting, fencing, and patrols, a high degree of security can be achieved.

To summarize my main points:

- standard magazine designs have both OCE blessing and DDESB blessing.

- our basic family of full-size magazines consists of:

    ° the concrete circular arch

- the steel circular arch
- the concrete oval arch
- the steel oval arch

- to select among these designs, one must consider function as well as cost.
- security is an inherent feature of an earth-covered magazine.

That concludes this paper.

* * * * * *

SYMBOL	DESCRIPTION	DATE	APPROVAL

REVISIONS

DEPARTMENT OF THE ARMY
OFFICE OF THE CHIEF OF ENGINEERS
MILITARY CONSTRUCTION - ENGINEERING DIVISION
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Fig. 1

DOD 5154.4S

DOD
AMMUNITION AND EXPLOSIVES SAFETY STANDARDS

Fig. 2

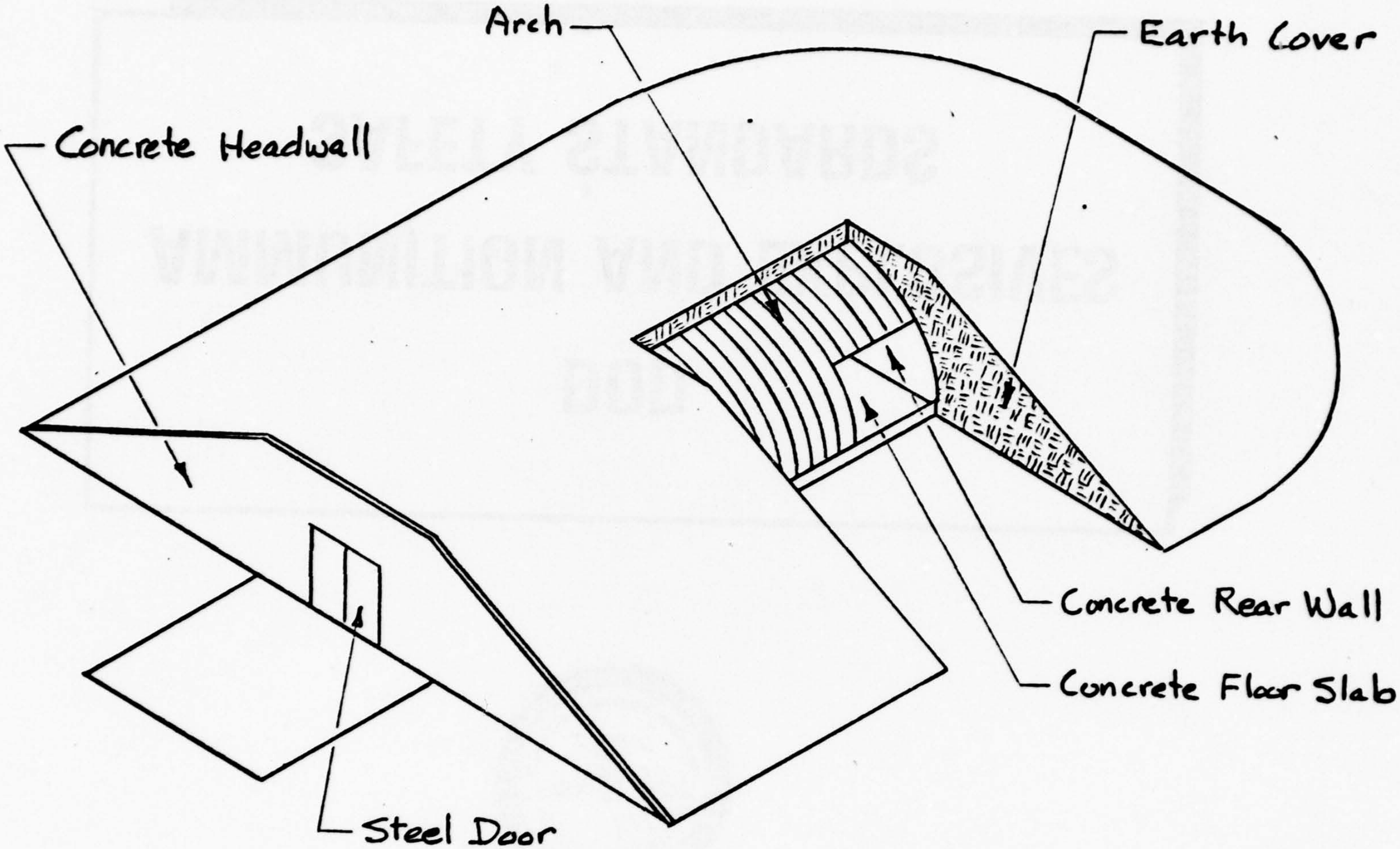


Fig. 3 Common Features of Magazines

Concrete Circular Arch Magazine

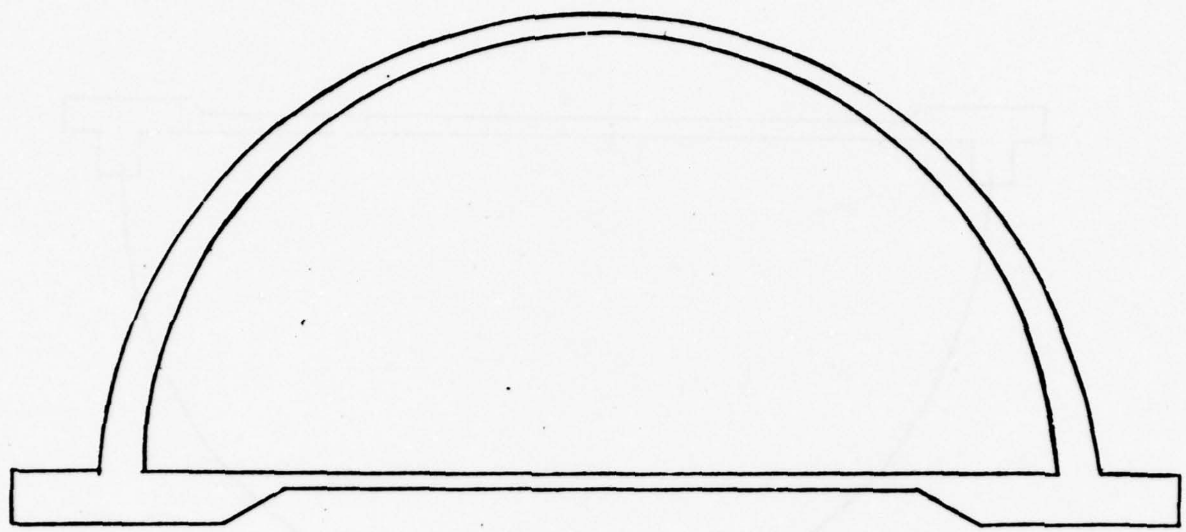


Fig. 4

Ref.: OCE Dwg. 33-15-06

Steel Circular Arch Magazine

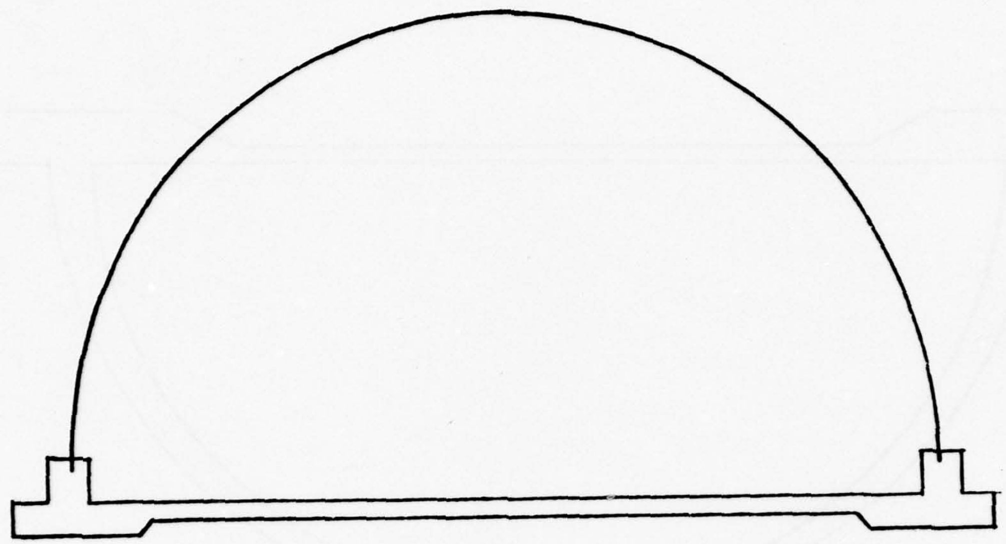


Fig. 5

Ref.: OCE Dwg. AW33-15-64

Steel Oval Arch Magazine

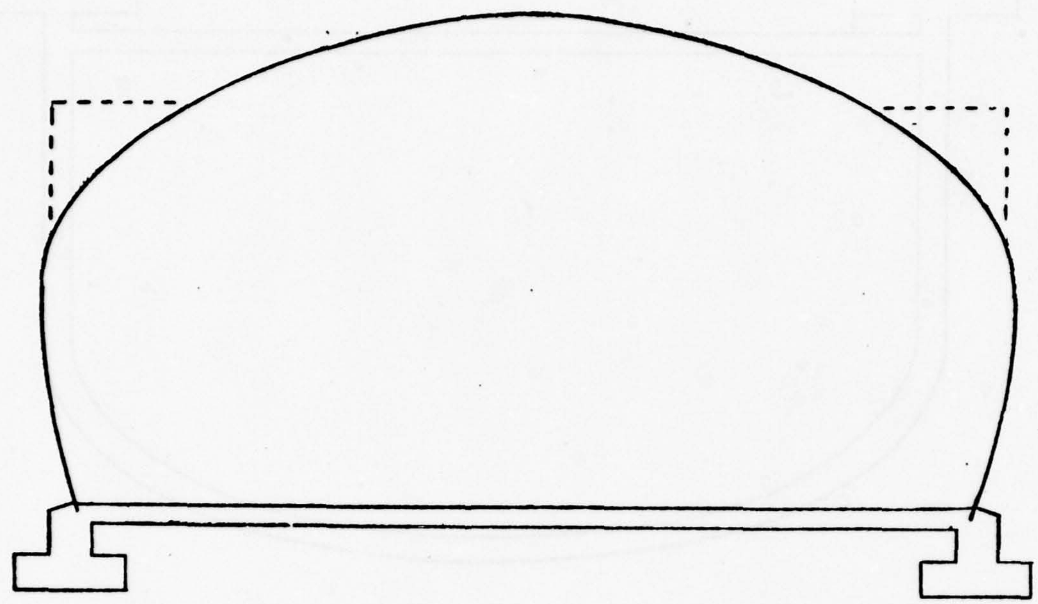


Fig. 6

Ref.: OCE Dwg. 33-15-73

Concrete Oval Arch Magazine

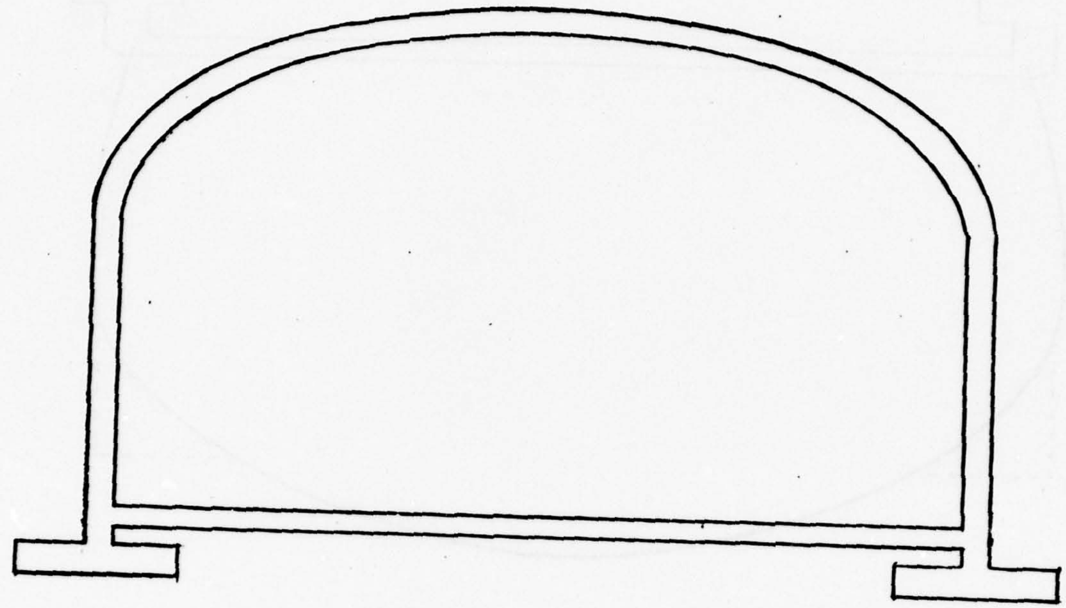
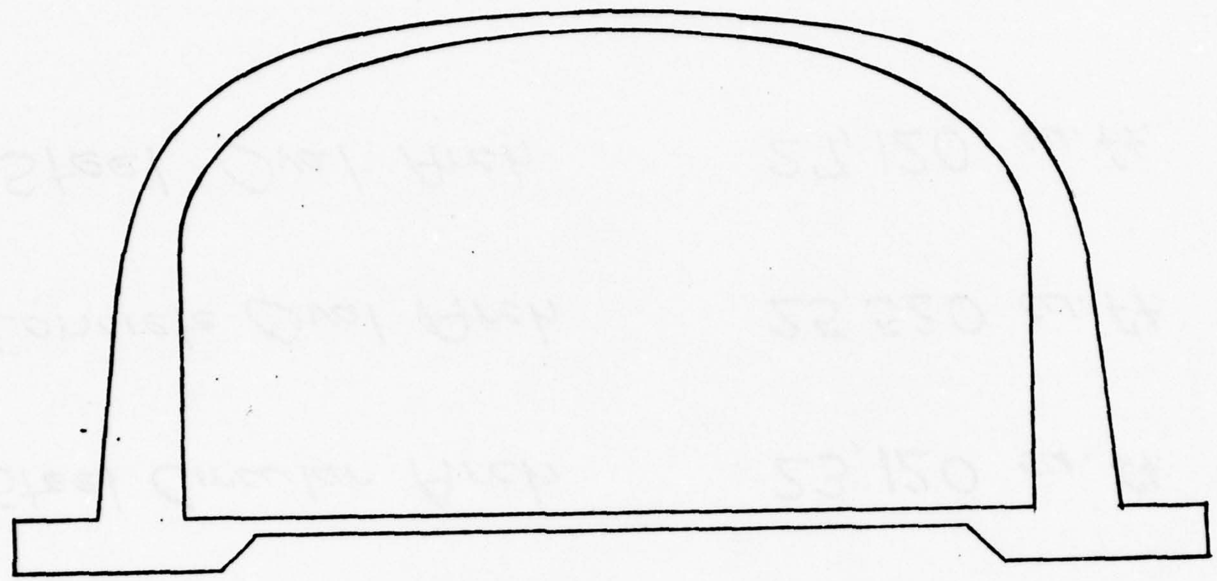


Fig. 7

Ref.: OCE Dwg. 33-15-74 (tentative)

Stradley Magazine



Ref.: OCE Dwg. 33-15-61

F:

Interior Volumes

• Concrete Circular Arch	21,360 cu. ft.
• Steel Circular Arch	23,120 cu. ft.
• Concrete Oval Arch	25,520 cu. ft.
• Steel Oval Arch	27,120 cu. ft.

Fig. 9

Comparison of Usable Volume

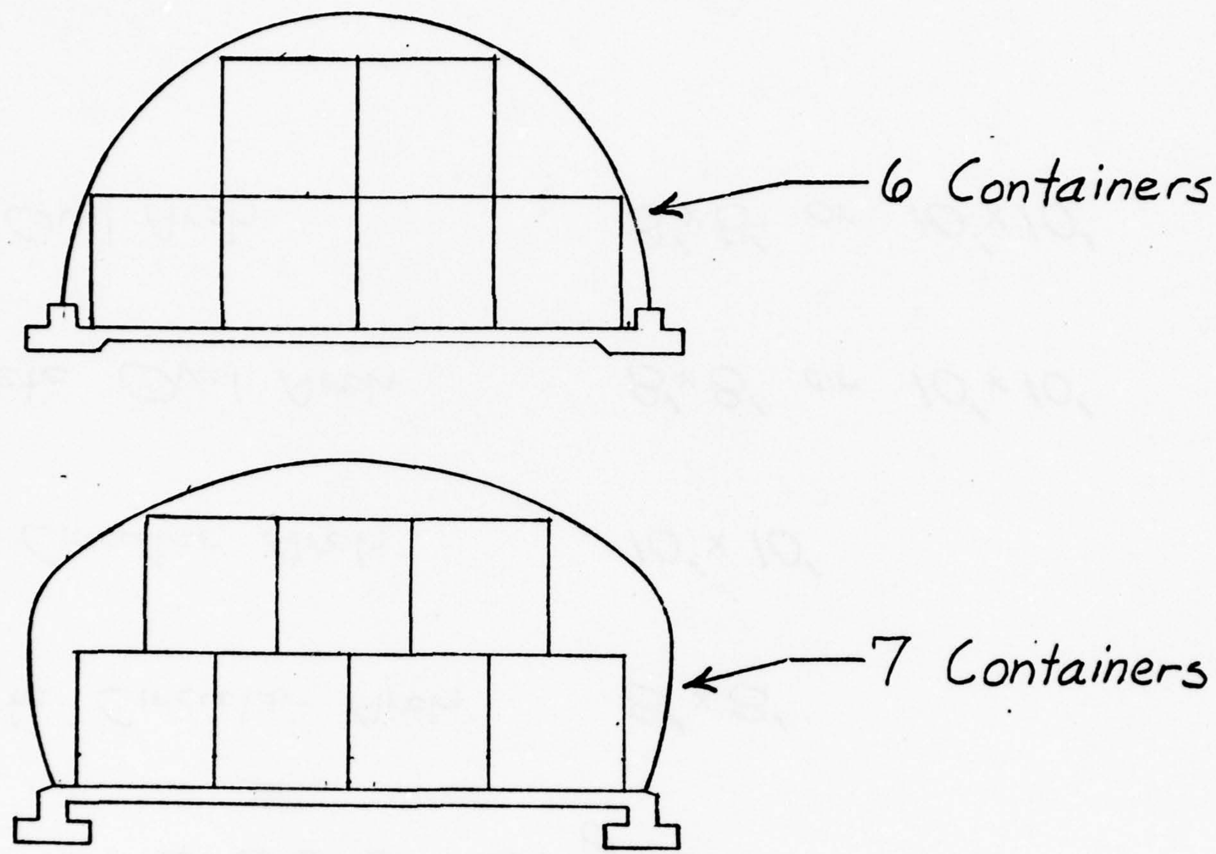


Fig. 10

Door Sizes

• Concrete Circular Arch	8′ x 8′
• Steel Circular Arch	10′ x 10′
• Concrete Oval Arch	8′ x 8′ or 10′ x 10′
• Steel Oval Arch	8′ x 8′ or 10′ x 10′

Fig. 11

Single Magazine Cost

• Concrete Circular Arch	$ 147,000
• Steel Circular Arch	$ 161,000
• Concrete Oval Arch	$ 171,000
• Steel Oval Arch	$ 179,000

Fig. 12

Cost per Cubic Foot of Volume

• Concrete Circular Arch	$ 6.87
• Steel Circular Arch	$ 6.95
• Concrete Oval Arch	$ 6.72
• Steel Oval Arch	$ 6.59

Fig. 13

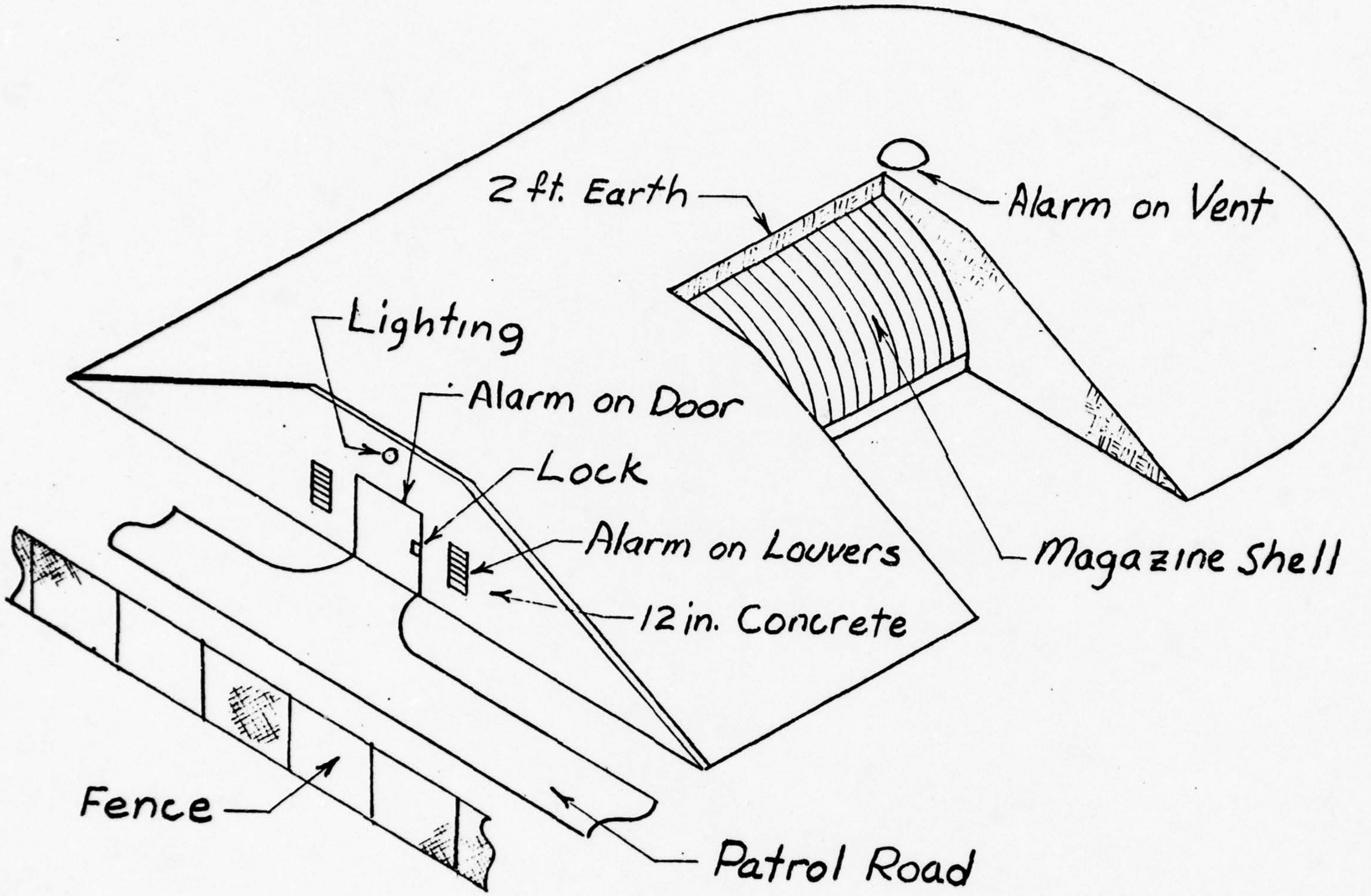


Fig. 14 Security Features of Magazines

AN ECONOMIC DECISION MODEL TO OPTIMIZE MAGAZINE DOOR DESIGN

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INTRODUCTION

Ordnance storage areas consist of one or more earth-covered structures designed and sited in accordance with minimum explosives safety standards in Chapter 5 of the NAVSEA OP-5 Pamphlet, Ammunition and Explosives Ashore. One standard requires a minimum spacing between individual magazines to limit the risk of an accidental explosion in one magazine from communicating to ordnance stored in any other magazine. The safety standards do not require a minimum strength for magazine doors.

In early years, typical storage in magazines consisted of conventional ammunition having a relatively low dollar value. However, sophisticated missile weapons systems developed in recent years have substantially increased the value of storage in Naval magazines. Should an accidental explosion occur in a magazine, in addition to the loss of that magazine, there is a risk that storage in neighboring magazines will also be lost as a result of the door being blown into its magazine by the blast pressures from the explosion..

The risk to contents in neighboring magazines can be decreased by increasing (hardening) the blast resistance of magazine doors. Is the increased cost of hardening the doors justified considering the low probability of an accident? Naval Sea Systems Command has funded CEL to develop an economic decision model to assist the Navy in choosing the optimum door design to minimize expected total cost.

OBJECTIVE

The objective of this study is to formulate an economic decision model for a rectangular array of magazines that will optimize door strength (to minimize expected total cost) as a function of content value, accident frequency, charge weight, depot size, and magazine design. Final results of this study will be published in a CEL Technical Note [1].

This paper briefly describes the decision model and provides specific results for various rectangular magazine arrays of up to 50 magazines oriented in the same direction with side separations of 1.25 $W^{1/3}$ and front to back separations of 2.86 $W^{1/3}$. Each earth covered magazine is 31 feet wide x 33 feet long with a headwall height of 19 feet. The net equivalent TNT charge weight in each magazine is 325,000 pounds.

The solution sensitivity to accident frequency levels and charge weight is investigated for a 4 x 10 array of 40 magazines at standard intermagazine distances (Front to Rear = 2 $W^{1/3}$; Side to Side = 1.25 $W^{1/3}$).

ECONOMIC DECISION MODEL

Earlier investigation by CEL [2] developed and tested an economic decision model for a single row of magazines. That study indicated that hardening magazine doors could significantly reduce the expected total cost over the economic life of a magazine depot.

The present study has expanded the capability of the model to a rectangular array of magazines of various orientations and has used the best available design information and state-of-the-art methods of analysis.

The basic algorithm is an equation for Expected Total Cost (ETC). The optimum door strength is determined by the minimum ETC. Figure 1 summarizes the information required to make this economic decision.

Expected Total Cost (ETC)

The ETC for each door strength and content value is the initial cost of the doors plus the present value of expected losses of doors and contents. Each magazine in the array is expected to have λ accidents in the 25-year economic life of the depot. The expected losses for a given strength door are thus the sum of all losses, with each magazine as a donor λ number of times in 25 years. A discount rate of 10% results in a discount factor (DF) of 0.381 if losses are averaged over each year of the 25-year economic life. (The guidelines in NAVFAC P-442 [3] were used in determining the discount factor and economic life.)

The equation for ETC is:

$$ETC = (N \cdot DC) + (DF \cdot \lambda) \cdot \left\{ \sum_{d=1}^{N} \sum_{a=1}^{N} \left[(DL \cdot DC)_d^a + (SL \cdot SC)_d^a \right] \right\} \quad (1)$$

where:

ETC = Expected Total Cost

N = Number of Magazines

DF = Discount Factor

λ = 25-Year Probability of an Event/Magazine

DC = Door Cost

SC = Content Value

$$DL = \begin{bmatrix} 0 \text{ if door survives} \\ 1 \text{ if door lost} \end{bmatrix}$$

$$SL = \begin{bmatrix} 0 \text{ if contents undamaged} \\ 1 \text{ if contents must be replaced} \end{bmatrix}$$

d = particular donor #

a = particular acceptor #

For a given set of conditions, ETC is calculated for each of several possible door strengths and the minimum ETC used to choose the optimum door strength.

Accident Probability

The accident probability (λ) was determined by C. E. Hart [4] of the Naval Surface Weapons Center, Dahlgren Laboratory. Mr. Hart surveyed Navy records and determined that 13 accidents had occurred in 359440 magazine years. This results in an accident frequency of one per 3.617×10^{-5} magazine years or, for the 25 year economic life of a depot, 9.042×10^{-4} accidents per magazine.

Depot Layout and Magazine Description

The depot is assumed to consist of a rectangular array of magazines in any number of rows and columns. The magazines may be oriented in the same direction or in alternate directions (front to rear and rear to front, etc.). The examples in this paper have the magazines oriented in the same direction as shown in Figure 2. Charge weight, content value, intermagazine separations, and magazine geometry are held constant for a given array. A range of content values may be specified to provide a solution for optimum door size as a function of content value.

A survey of magazine door costs [5] led to the following relationship for the present value of the 26 x 16 foot door used in the examples.

$$DC = 1950\ (r_u)^{0.43} \text{ dollars} \qquad (2)$$

Where r_u is the ultimate door strength in psi.

Blast Environment

The blast pressures and impulses from an explosion in an earth covered magazine are very directional. Scaled data from tests by Charles Kingery of BRL [6] along lines at 0^o, 90^o, and 180^o from a donor magazine are used to determine the peak incident pressure and

impulse at each acceptor. The methods and information in NAVFAC P-397 [7] are then applied to determine dynamic pressure, reflected pressure, reflected impulse, and duration of the positive phase. A bilinear pressure-time loading fucntion may result from a combination of the incident and reflected waves. At high pressure regions, or where reflected pressures are not developed, the pressure-time loading will be linear. Figure 3 shows these possible conditions.

Door Response

The door response is based on a single degree of freedom elasto-plastic resistance function as shown in Figure 3. The strength (r_u), stiffness (r_u/X_e), and natural period (T_n) are found using yield line theory. An analysis [5] of a 26 x 16 foot steel door, supported on 3 sides, constructed of I-beams and cover plates, resulted in the following relationship for $0.3 \leq r_u \leq 50$ psi:

$$X_e = 44\ (r_u)^{-0.73} \text{ inches} \quad (3)$$

$$T_n = 415\ (r_u)^{-0.69} \text{ milliseconds} \quad (4)$$

(The minimum door strength is designed for standard windloads, while the maximum strength door will protect magazine contents against the effects of an explosion of 500,000 pounds in an adjacent magazine. Twenty seven other door strengths are included between these limits to accurately determine the optimum.)

Maximum deflection (X_m) is computed for each acceptor door by solving the differential equations for the dynamic response of the single degree of freedom system having the resistance and loading functions shown in Figure 3.

Failure Criteria

The ratio of maximum deflection (X_m) to the elastic deflection limit (X_e) is found for the door at each acceptor for an explosion in each donor. This ratio is compared with preselected performance limits on X_m/X_e to determine when a door must be replaced and when contents are lost. For this study, when X_m/X_e exceeds 2, the door is considered a loss (nonreusable) because of the amount of permanent deflection; and when X_m/X_e exceeds 10, it is assumed that the door is blown into the magazine and that the contents need replacement. The summation of the doors lost and the contents lost are then used in the equation for total cost.

Data Output

The results of the decision model are displayed in a series of tables (one for each of the content values checked) that list door and

content losses and expected total cost for each door strength. Figure 4 shows selected listings for an example problem. Results may also be displayed in a three-dimensional plot as shown in Figure 5. The savings-to-investment ratio, commonly used to compare alternate choices, may be calculated from the expected total costs and door values.

SAMPLE PROBLEM

Given

(See Figure 2 for depot layout and magazine geometry)
40 magazines (4 rows x 10 columns)
Size: 31 x 83 feet with a 19 foot high headwall
Spacing: 1.25 $W^{1/3}$ (Side to Side)
2.86 $W^{1/3}$ (Front to Back)
Net Explosive Weight: 325,000 pounds
Content Value: \$10,000,000/magazine
Door Size: 26 x 16 feet (Simply supported at top and two sides)
λ: 9.04×10^{-4} explosive/magazine life
Economic Life: 25 years
Discount Rate: 10%

Problem

Find the optimum door strength to minimize expected total cost over the life of the depot.

Solution

The economic decision model, with the algorithms previously described, gives a minimum expected total cost at a door strength of 34 psi. Selected losses and ETC's, as a function of door strength, are listed in Figure 4. With the optimum door, total door losses (corresponding to one accident in each magazine) are 274 and total content losses are 40 (donors only). The expected losses (0.25 doors and 0.04 contents) reflect the actual probability of λ accidents/magazine life. The Expected Total Cost is the sum of the initial cost of 40 doors plus the present values of the expected losses. The data shows that although the 50 psi door would reduce expected door losses, the Expected Total Cost would be higher because of the greater initial door costs.

Figure 5 shows ETC versus r_u for a range of content values between 0.1 and 10 million dollars. ETC is shown as a surface defined by dashed lines in planes of constant content value. A vertical plane is marked along the optimum path. A plan view of the optimum path would show optimum door strength versus content value. The minimum ETC as a function of content value is projected onto the right side of the plot. It can be seen that for content values above \$2.8 million the 34 psi door is optimum. For content values below \$0.3 million, the minimum strength door is optimum. Other doors would be the best choice at values between these limits.

Savings-to-Investment Ratio (SIR)

The benefits of a given door strength are measured by the savings-to-investment ratio. In the sample problem, with the content value at \$10 million, the ETC for the optimum door is \$0.49 million. The expected savings in ETC, by choosing to harden the door rather than use the minimum door, is \$5 million. The investment is the difference between the initial costs of the two doors for 40 magazines (\$0.31 million). This results in an SIR of 16. Figure 6 shows this calculation and provides the optimum ETC and unhardened door ETC as functions of content value. Choice of a hardened door will provide an SIR greater than 1 at all content values exceeding \$0.3 million.

PARAMETER SENSITIVITY

Array Size

The size of the magazine array was varied to study its effect on the optimum door design. Figures 7 and 8 display optimum door strength versus content value for different sizes of 2 and 4 row depots. These results show that, as the number of magazines increases, the value of magazine contents for which hardened doors would be cost effective is reduced. The range of content values for which the optimum solution falls between the minimum and maximum door strength is also expanded.

Figure 9 compares results for 40 magazines in two arrays (4 x 10 versus 2 x 20). Adding columns, rather than increasing rows, reduces ETC and also has the effects noted above for increasing the number of magazines (reducing content value at which hardening is cost effective and expanding the range of content value at which the optimum door size is between the minimum or maximum strength).

Charge Weight

The sample problem values were used with standard intermagazine separations (FB = $2.0\ W^{1/3}$, SS = $1.25\ W^{1/3}$) to test the effect of charge weight on optimum door strength. The results for 150,000, 325,000, and 500,000 pound donor charge weights are shown in Figure 10. Reducing the charge weight, while keeping the scaled intermagazine separations constant, reduced the minimum content value at which hardening the door would be beneficial. It also reduced the door size needed to protect the contents in the acceptor magazines immediately adjacent the donor. Therefore, the maximum optimum door strength at high content values is reduced with reductions in design charge weight.

Expected Frequency of Explosions

The sample problem values were used with standard intermagazine separations to study the influence of explosion frequency on optimum

door strength. Since the objective of this study is to optimize door strength by minimizing cost, the observed number of accidents is the best estimate of future accident frequency. Any other value would reduce the accuracy of the solution. Confidence levels may still be useful to the designer, however. Figure 11 shows the solutions for this problem with the measured λ and $\lambda \pm \sigma$. The confidence level in the optimum solution depends on the content value. At content values below $0.26 million and above 2 million, the confidence in the optimum solution would be high.

CONCLUSION

Hardening magazine doors can significantly reduce the Expected Total Cost over the economic lives of magazine depots. The economic decision model being developed by CEL provides a rational basis for determining benefits versus hardness and for choosing the optimum door strength.

ACKNOWLEDGMENTS

Mr. Robert Thompson began this study and is responsible for adapting the engineering relationships to the computer decision model. Rita Brooks and Nathan Shoemaker supplied most of the computer programming. Max Eaton and Jerry Hopkins provided valuable mathematical and statistical guidance. Bill Keenan assisted during all phases of the study.

The author gratefully acknowledges the contributions by these members of the CEL staff.

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2. Civil Engineering Laboratory. Technical Memorandum TM-51-77-08: Optimum Design of Magazine Doors, by M. L. Eaton and N. F. Shoemaker, Port Hueneme, CA.

3. Navy Economic Analysis Handbook. NAVFAC P-442, June 1975.

4. Naval Surface Weapons Center. Letter Report: The Probability of an Accident in a Naval Magazine Ashore, by C. E. Hart, Dahlgren, VA, Feb 1978.

5. Letter Report by G. R. Swihart, Sep 1977.

6. Army Ballistics Research Laboratory. Memorandum Report No. 2680: Blast Parameters from Explosions in Model Earth Covered Magazines, by C. N. Kingery, G. A. Coulter and G. T. Watson, Aberdeen Proving Ground, MD, Sep 1976.

7. Army, Navy and Air Force. TM 5-1300/NAVFAC P-397/AFM 88-22: Structures to Resist the Effects of Accidental Explosions, Washington, D.C., Jun 1969.

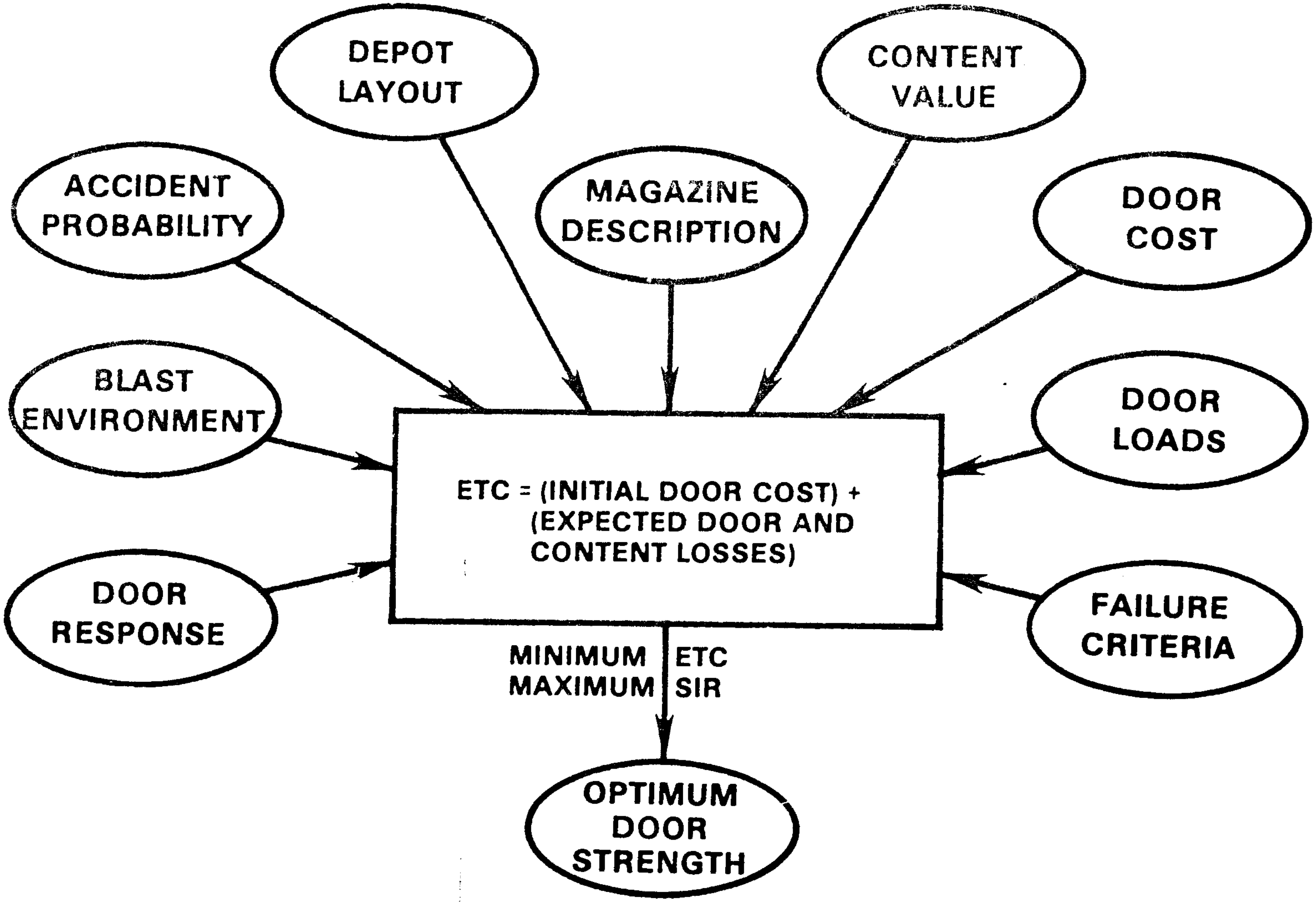

Figure 1. Information Required for the Economic Decision Model.

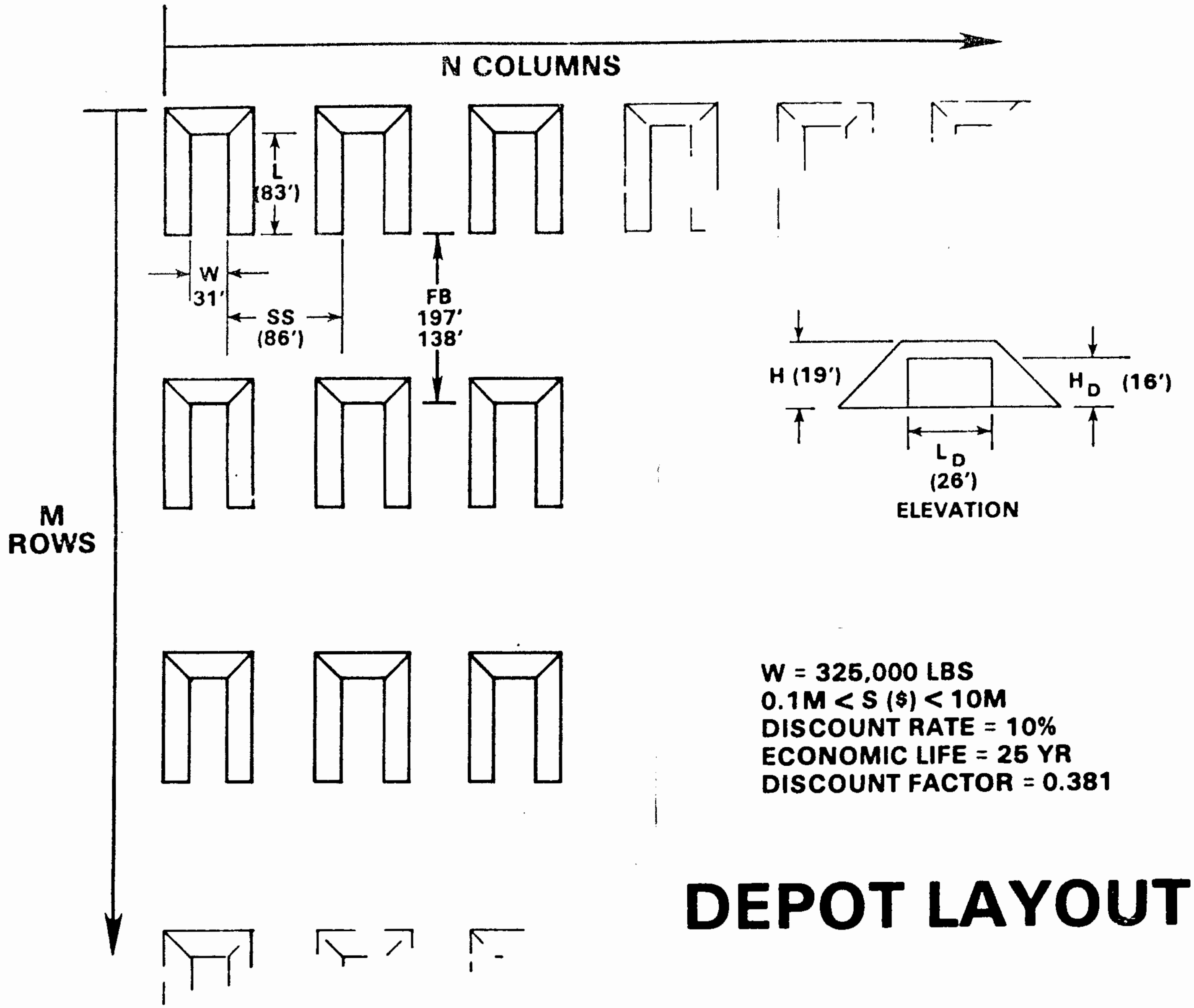

Figure 2. Depot Layout and Magazine Geometry.

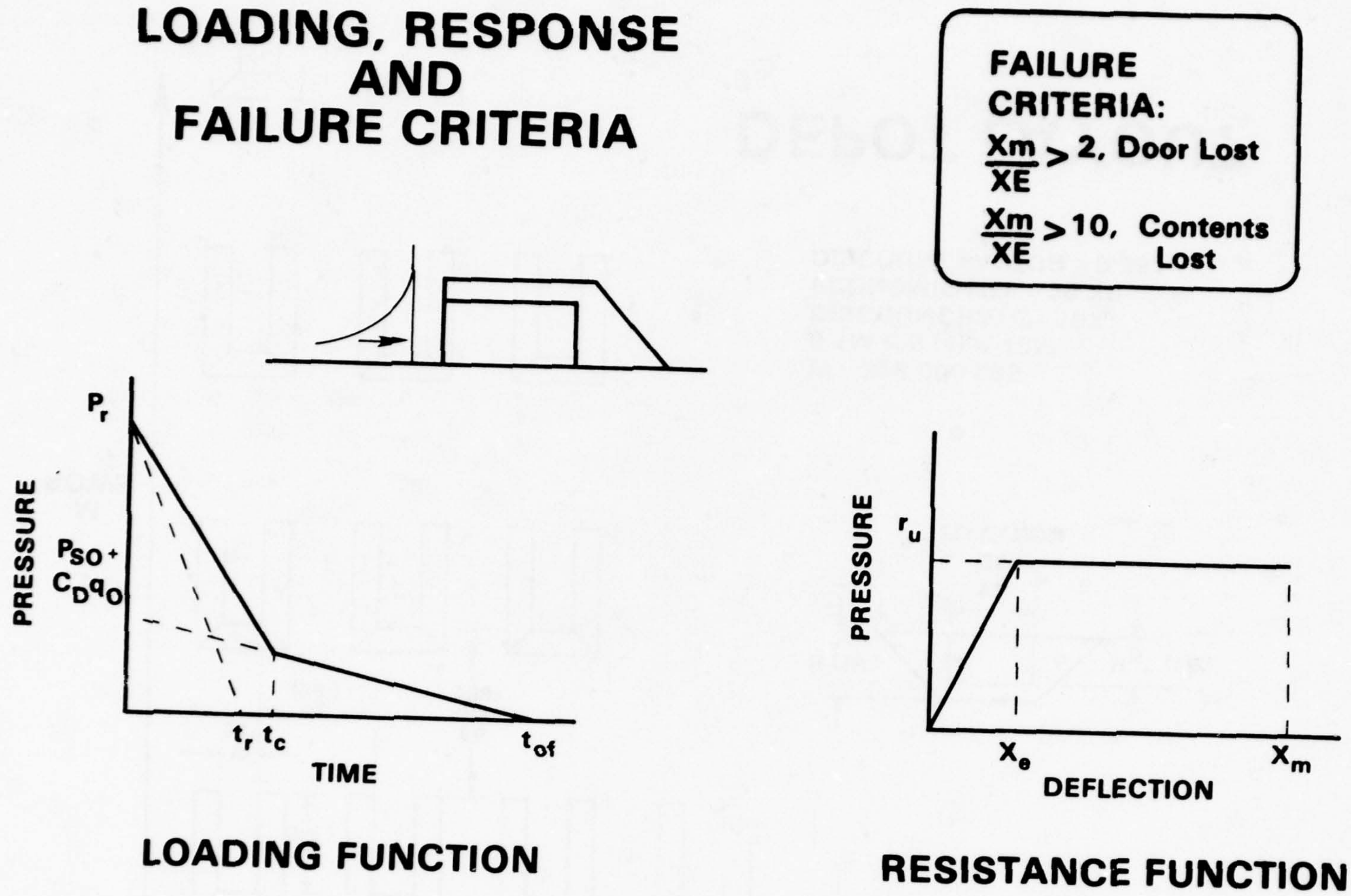

Figure 3. Door Loading, Response and Failure Criteria.

LOSSES AND ETC'S FOR 4x10 ARRAY

(SS=1.25$W^{1/3}$,FB=2.86$W^{1/3}$,W=325,000)

DOOR STRENGTH (r_u),psi	NUMBER OF LOSSES (EACH MAGAZINE A DONOR)		EXPECTED LOSSES (λACCIDENTS)		ETC SC=10M (DOLLARS)
	DOORS (DL)	CONTENTS (SL)	DOORS (λDL)	CONTENTS (λSL)	
0.3	1600	1600	1.44	1.44	5.56M
1.7	1600	1148	1.44	1.04	4.05M
5.0	1314	494	1.19	0.45	1.86M
9.0	952	328	0.86	0.30	1.33M
20.0	464	118	0.42	0.11	0.69M
34.0	274	40	0.25	0.04	0.49M
50.0	112	40	0.10	0.04	0.55M

Figure 4. Selected Data Output from the Economic Decision Model.

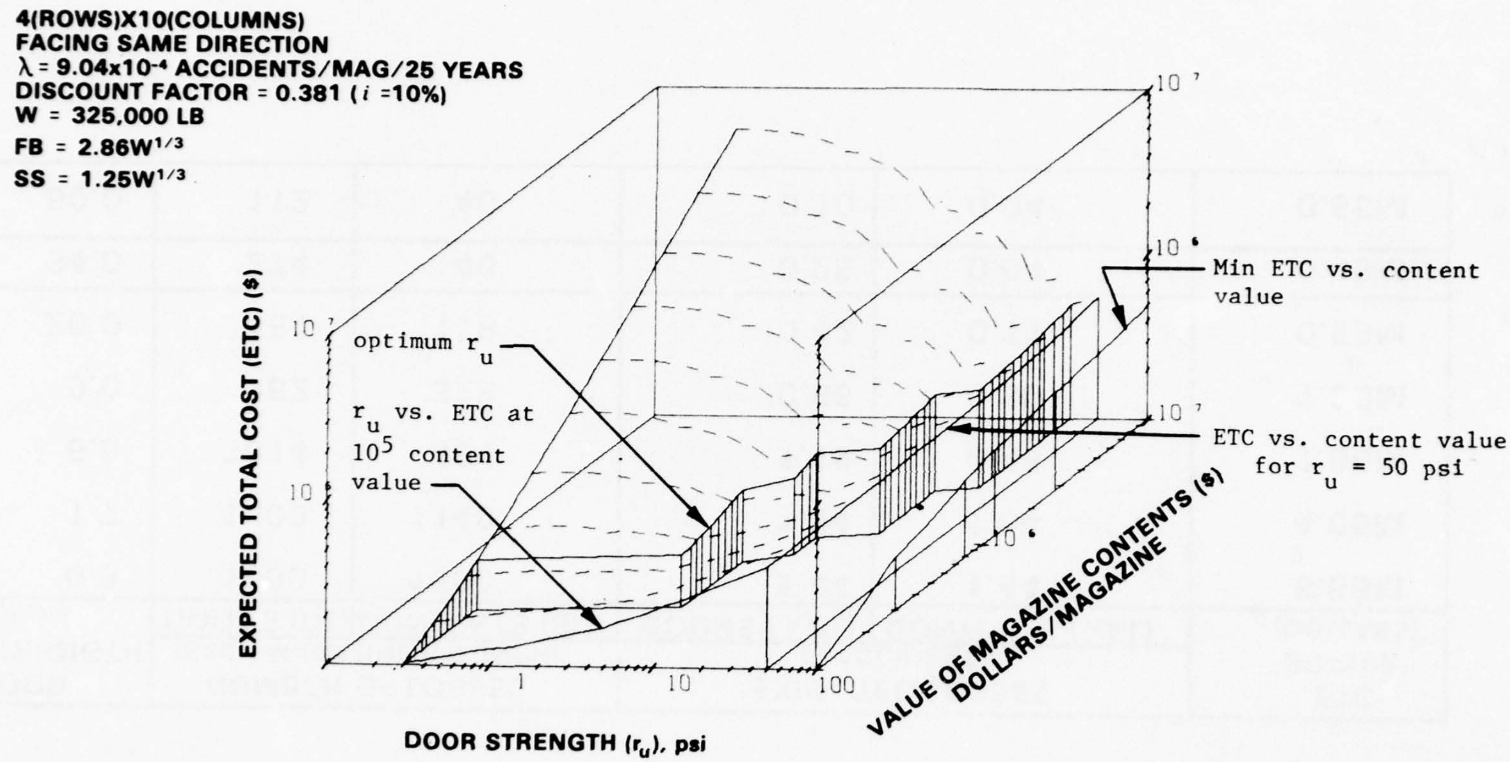

Figure 5. 3-D Plot of Data Output.

SAVINGS TO INVESTMENT RATIO

FOR A 4X10 ARRAY,

EXPECTED NO. OF ACCIDENTS (IN 25 YEAR LIFE)	9.04×10^{-4}/MAG
VALUE OF CONTENTS/MAGAZINE	$10M/MAG
DISCOUNT FACTOR (i = 10% FOR 25 YEARS)	0.381
ETC WITH UNHARDENED 0.3 psi DOOR	$5.56M
ETC WITH OPTIMUM 34 psi DOOR	$0.49M

THE ADDITIONAL INITIAL INVESTMENT FOR THE OPTIMUM DOOR VS. THE UNHARDENED DOOR IS,

I = (8883 - 1162)$/MAG X 40 MAG
I = $0.31M

THE RESULTING SAVINGS TO INVESTMENT RATIO IS,

$$\text{PAYOFF} = \frac{\$5.56 - \$0.49}{\$0.31}$$

$$= \frac{\$16 \text{ SAVED}}{\$1 \text{ INVESTED}}$$

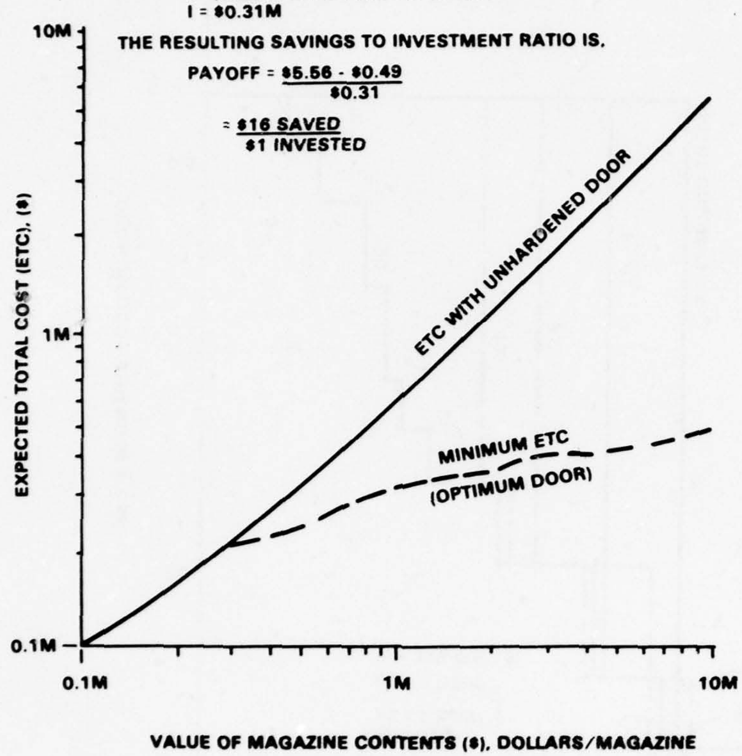

Figure 6. Savings to Investment Ratio with Optimum Door (40 Magazines, SC = $10 Million).

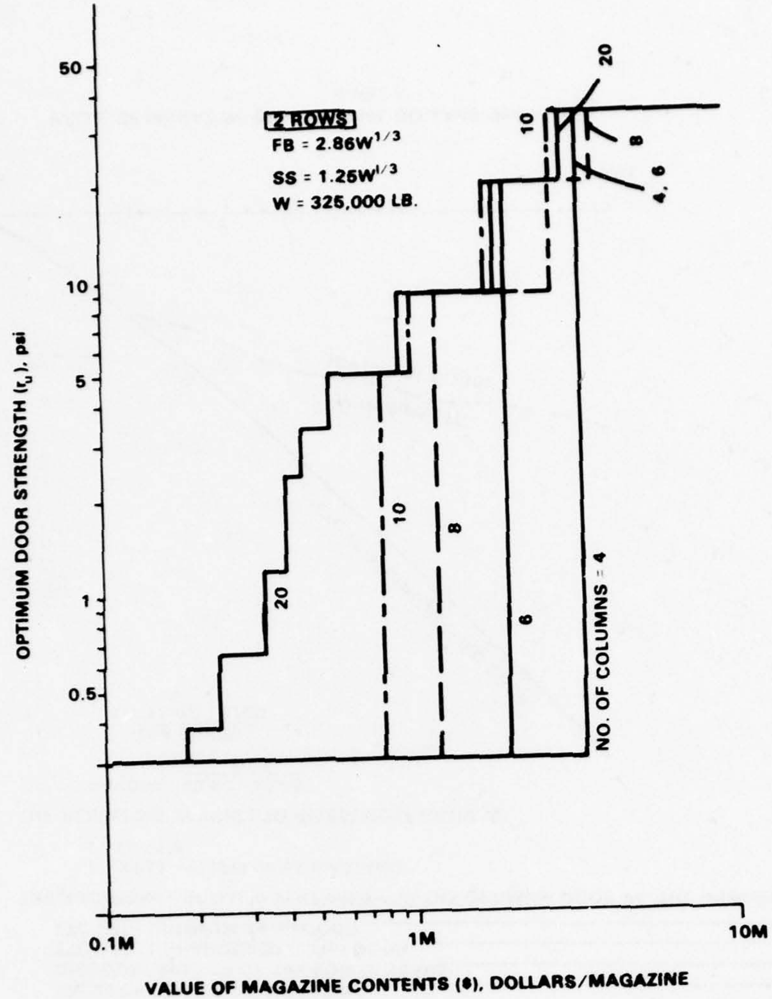

Figure 7. Optimum Door Strength vs. Value of Magazine Contents for 2 Rows of Magazines.

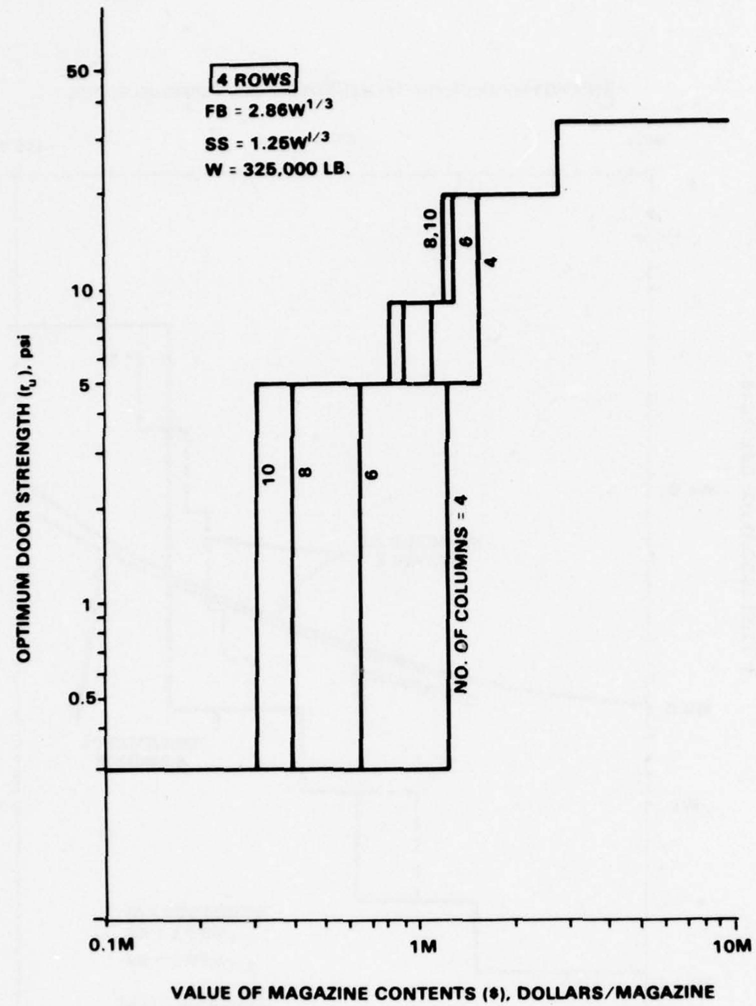

Figure 8. Optimum Door Strength vs. Value of Magazine Contents for 4 Rows of Magazines.

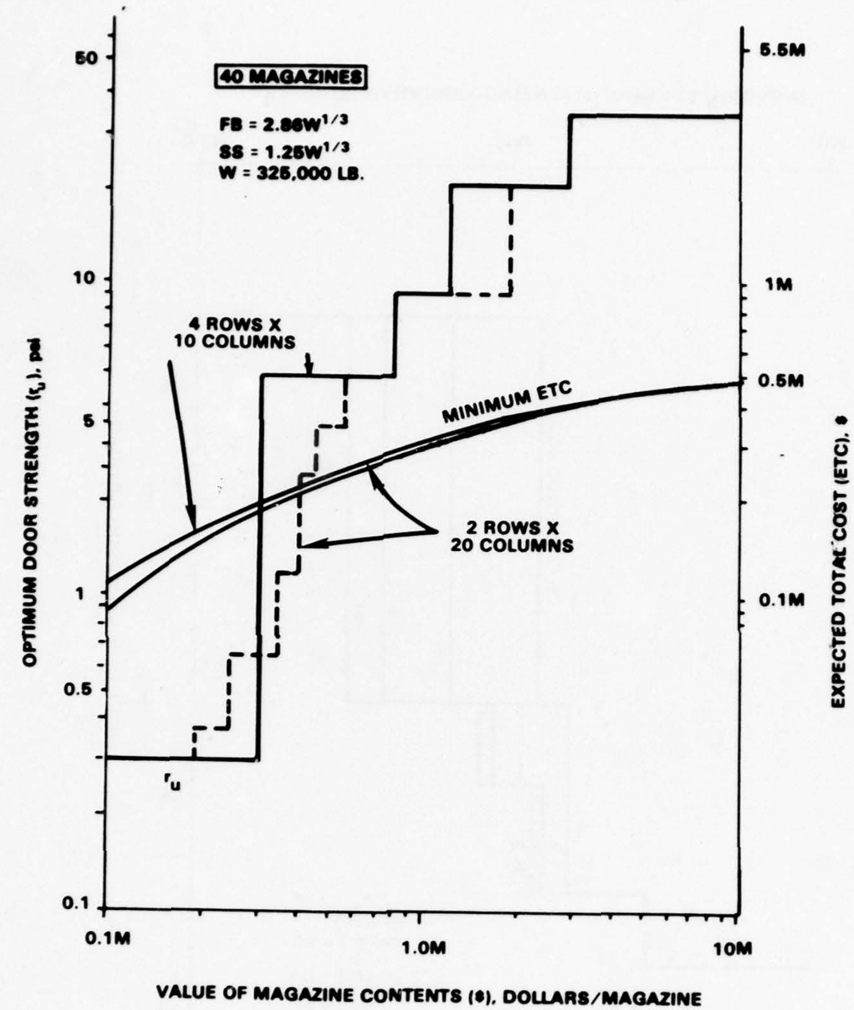

Figure 9. Optimum Door Strength for 40 Magazines in 4 x 10 and 2 x 20 Arrays.

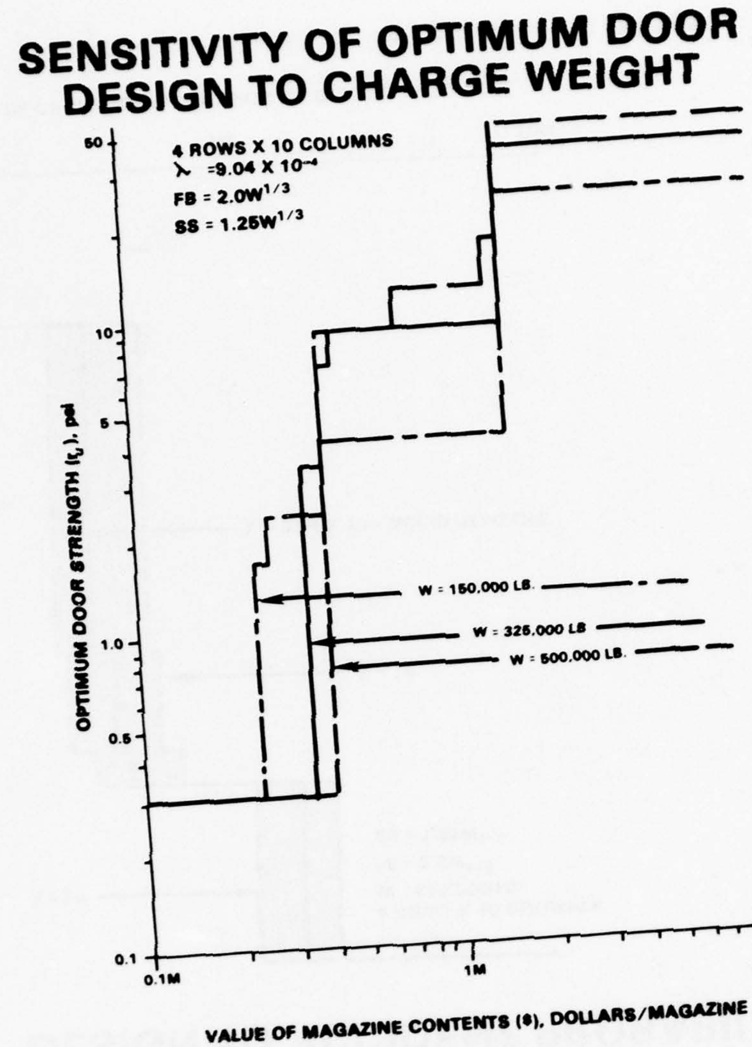

Figure 10. Effect of Charge Weight on Optimum Door Design.

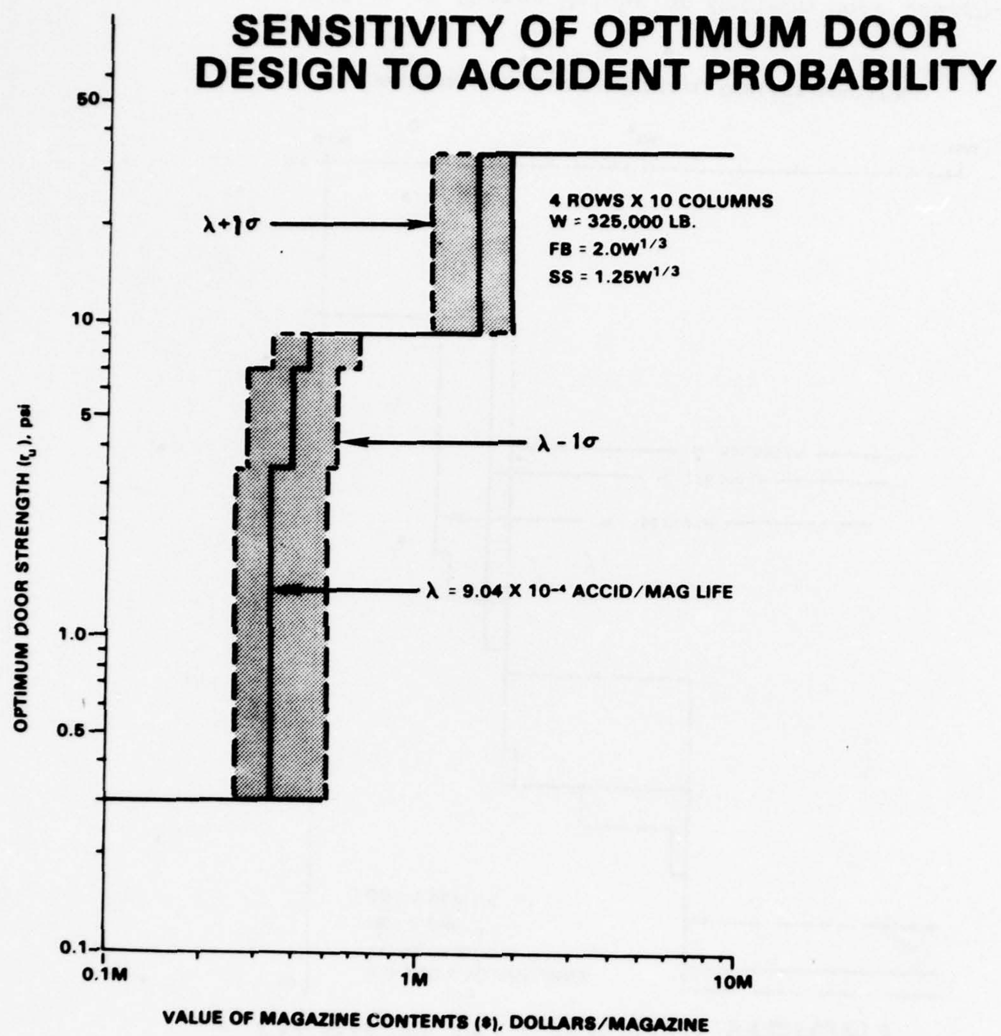

Figure 11. Effect of Accident Probability on Optimum Door Design.

EFFECT OF EARTH-COVER ON THE DONOR-IGLOO TO AIRBLAST IN THE NEAR FIELD REGION

by

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ABSTRACT

Apparent differences are found in various test programs between the results of blast measurements at the acceptor headwall in the quantity distance 0.8. $Q^{1/3}$ to the rear of a donor igloo. This report summarizes the data from full-scale and model tests. It will be shown that the equivalent weight correction for elongated, cased, non TNT explosive charges does not provide satisfactory explanation for the different test results. The application of blast scaling shows, that the measurements were taken in decreasing scaled distances from ground zero with increasing charge weight, thus explaining increasing pressure within individual test series. For the interpretation of the remainig differences between various test programs it is suggested to take into consideration different donor arch thickness by using a scaled cover parameter.

I. INTRODUCTION

Starting in 1971 various igloo test programs were performed in different contries in order to determine the blast load on adjacent igloos. The special topic of this paper is the regular reflected peak overpressure on the bottom of the acceptor headwall at the quantity distance $D = 0.8 \cdot Q^{1/3}$ in front-to-rear arrangement (Figure 1). Reported pressure values range from 5 bar to 18 bar. An attempt is made to interpret the apparent differences in different test program results and to find a format of data presentation which may reduce the available dato to more functional relationships.

II. BLAST SCALING

The Figure 2 summarizes the test arrangements from Prototype and model tests. The tests were performed in different model scales 1 : 1 to 1 : 50 with different explosive quantities. All charge weights are recalculated full-scale data and net explosive quantities.

The most common form of scaling data from model to prototype is "cube-root" scaling. This law states that self-similar blast waves are produced at identical scaled distances when two explosive charges of similar geometry and the same explosive, but of different size, are detonated in the same atmosphere.

As a matter of fact not all of the different test programs are planned on the basis of blast scaling and a host of deviations from basic scaling requirements is to state. The differences can be summarized to four groups:

1. Different blast sources in various test programs e.g. type of explosive, case and shape of source.
2. Ambient conditions.

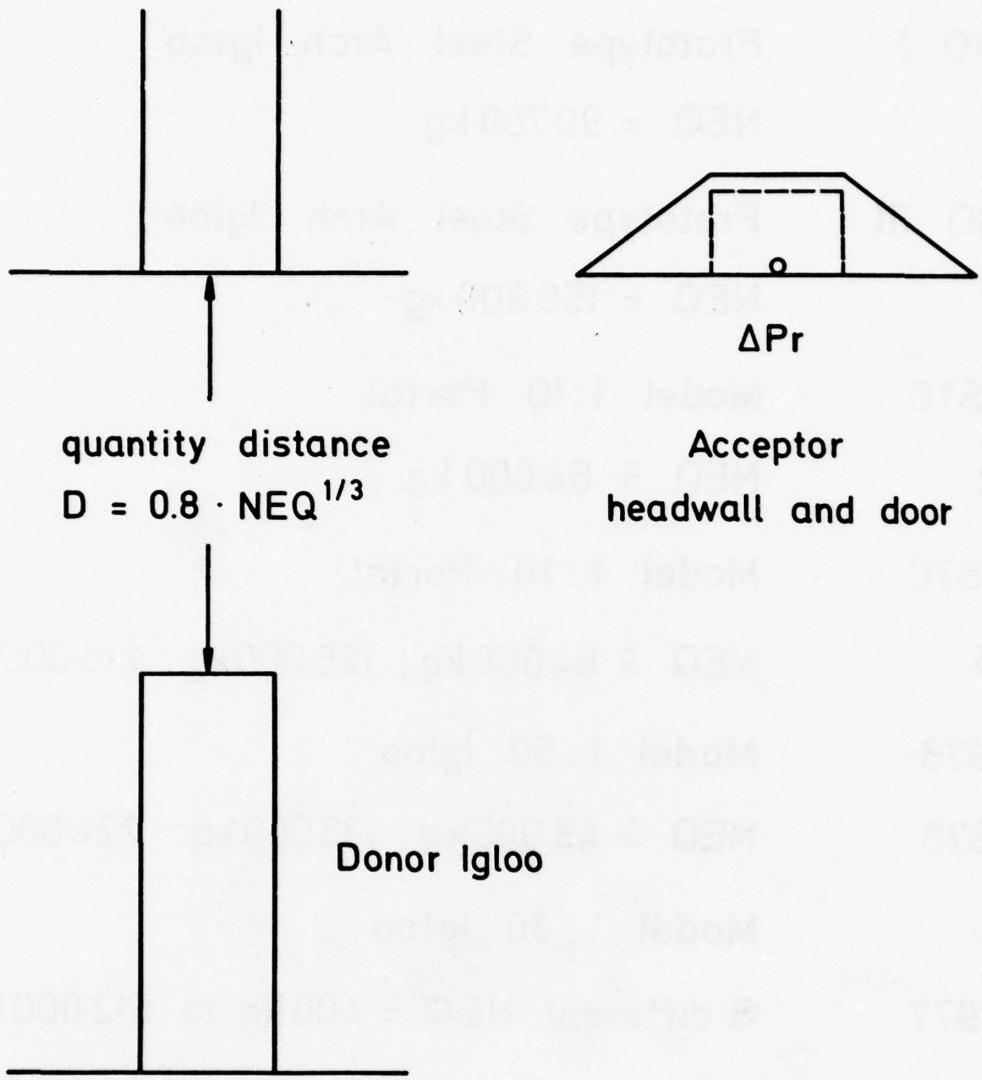


Fig. 1

Air Blast from Earth - Covered Magazines:

Regular reflected peak overpressure on the bottom of the acceptor headwall at quantity distance $0.8 \cdot Q^{1/3}$ front - to - rear

ESKIMO I	Prototype Steel Arch Igloo
1971	NEQ = 90 700 kg
ESKIMO III	Prototype Steel Arch Igloo
1974	NEQ = 158 900 kg
UK-ESTC	Model 1:10 Portal
1972	NEQ ≙ 64 000 kg
UK-ESTC	Model 1:10 Portal
1976	NEQ ≙ 64 000 kg; 125 000 kg; 216 000 kg
BRL 1976	Model 1:50 Igloo
BRL 1978	NEQ ≙ 45 000 kg; 133 000 kg; 224 000 kg
NDCS	Model 1:30 Igloo
1976/1977	8 different NEQ ≙ 400 kg to 512 000 kg
SWISS	Model 1:10 Slightly Buried Magazine
1975/1976	8 different NEQ ≙ 50 kg to 50 000 kg

Fig. 2

Air Blast from Earth - Covered Magazines

Summary of Test Arrangements

3. Ground plan and cover of donor igloos are not scaled according to charge weight within single test programs.
4. Different construction of donor igloos in various test programs e.g. ground plane and cover.

The differences in test arrangements must be taken into consideration in order to compare the test results on the basis of "cube-root" scaling.

III. EQUIVALENT WEIGHT

The charges inside the donor igloos are elongated, cased non-TNT blast sources. Methods for equating the blast effects of charges in igloos to those of an idealized TNT charge are required for the comparison of test results on the basis of "cube-root" scaling. The Figure 3 points to the fact, that different types of explosives were used in various test programs. One can approximately equate blast waves from different explosives by using a conversion to an equivalent weight of some standard explosive, usually TNT. Although blast parameters are measurably different for different explosives, the entire range of differences is not great.

Secondly, a method to determine the effects on airblast of a metal casing, surrounding the cylindrical charges of bombs and projectiles, is required. The Figure 4 represents the different case weight to charge weight ratios belonging to the prototype charges. Bare charges are used with all model tests. The casing factor formula used in current U.S. conventional weapons effect handbooks is taken to calculate a casing equivalent weight factor. Though not exact, this method offers a way of estimating blast for explosives where limited data exist.

ESKIMO I	TNT
ESKIMO III	Tritonal (f_e = 1.13)
UK - ESTC	Tetryl / TNT
BRL	Cast Pentolite (f_e = 1.06)
NDCS	TNT / PETN
SWISS	TNT

Blast Source Energy Correction :

Empirical energy equivalency weight factors are used to approximately equate blast waves from different explosives to an equivalent weight of some standard explosive, usually TNT.

$$Q_{TNT} = f_e \cdot Q$$

Effect on Quantity Distance :

max. 4% at f_S = 1.13 ESKIMO III

Fig. 3 Variation of Explosives

ESKIMO I 155mm - Projectils $\frac{M}{Q} \sim 5$

ESKIMO III M 117 - Bombs $\frac{M}{Q} \sim 1$

Bare charges with all model tests

Casing Correction:

Empirical casing equivalent weight factors are used to approximately equate blast waves from cased explosives to an equivalent weight of bare charges.

$$Q_{eff} = f_s \cdot Q$$

Effect an Quantity Distance:

No data available for large stacks inside Igloos

Fig. 4

Variation of Blast Source Metal Casing

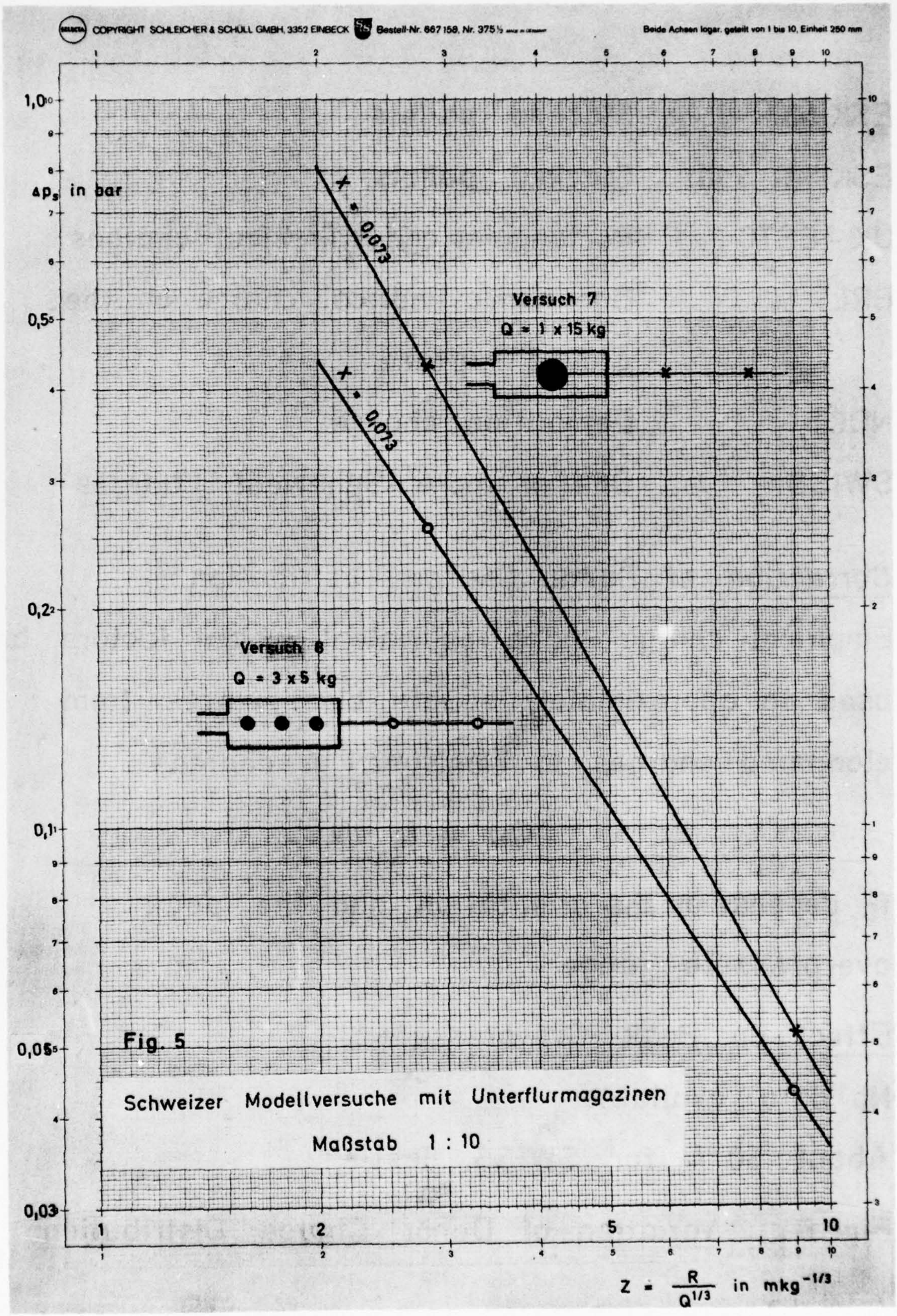
As an example for the effect of different charge shape in the donor igloo does Figure 5 show the peak overpressure as a function of scaled distance for two different charge distributions inside the Swiss magazine at equal total charge weight. The difference in peak pressure depends on the overpressure level and comes up to a factor of 2 at 1 bar. No measurements are made at higher pressure level. Different charge distributions at different igloo test arrangements are compiled in Figure 6. No data are available for charge shape equivalent weight factors for igloo arrangements.

Regular reflected peak overpressures at quantity distance 0.8. $Q^{1/3}$ as a function of the charge weight for three different test programs are put together in Table 1. Within each arrangement does the peak overpressure increase with increasing charge weight and there are differences in peak pressure from one program to another at similar explosive quantities. Since the equivalent weight correction is taken into consideration we have to recognize, that it does not provide satisfactory explanation for the different test results.

Table 1

Regular reflected peak overpressure at quantity distance 0.8. $Q^{1/3}$ as a function of the charge weight.

ESTC 1976		NDCS 1976		BRL 1978	
Q in kg	Δpr in bar	Q in kg	Δpr in bar	Q in kg	Δpr in bar
64.000	7.3	70.000	9	44.583	10.2
125.000	8.4	130.000	14,5	133.290	10.4
216.000	9.4	513.000	15	224.000	12.1


COPYRIGHT SCHLEICHER & SCHÜLL GMBH, 3352 EINBECK
Bestell-Nr. 667158, Nr. 375½
Beide Achsen logar. geteilt von 1 bis 10, Einheit 250 mm
Δp_s in bar
1,0
0,5
0,2
0,1
0,05
0,03
X = 0,073
X = 0,073
Versuch 7
Q = 1 x 15 kg
Versuch 8
Q = 3 x 5 kg
Fig. 5
Schweizer Modellversuche mit Unterflurmagazinen
Maßstab 1 : 10
1
2
5
10
$Z = \frac{R}{Q^{1/3}}$ in $mkg^{-1/3}$

ESKIMO I	Stacked pallets
ESKIMO III	Stacked pallets
UK - ESTC	Rectangular and cylindrical charges
BRL	One hemicylindrical charge on the ground surface
NDCS	Demolition charge
SWISS	One or more Spherical Charges

Correction of Donor Charge Distribution :

Empirical charge shape equivalent weight factors are used to approximately equate blast waves from elongated charges to hemispherical charges

$$Q_H = f_S \cdot Q$$

f_S depends on the orientation and the peak overpressure range

Effect on Peak Overpressure :

No data available

About 50 % for SWISS Test

Fig. 6 Variation of Donor Charge Distribution

IV. AMBIENT CONDITIONS

It is noted that the ESKIMO prototype tests have not been conducted at sea level conditions. No attempt is made in this paper to account for the changes in ambient conditions.

V. GROUND PLAN

The Figure 7 summarizes the donor ground plans in various test programs, all recalculated to full scale data. Since geometric similarity of the experiments is not maintained, blast parameters may vary at 0.8. $Q^{1/3}$ quantity distance even with equal charge weight for e.g. 18 m and 24 m igloos. It is outlined in Figure 8 that the difference in igloo length amounts to about 10 percent of the quantity distance and a measurable effect on blast is to be expected.

Equal distance from rear walls results in equal blast parameters very close to the wall. Equal distance from donor centers is correct for far field measurements. The real situation at quantity distance $D = 0.8. Q^{1/3}$ is expected to be somewhat between.

As explained in the "Scaled Distance" section it is suggested to measure all distances from the center of the blast source and to neglect different ground plans. It is felt that a geometric shape correction should be used, but not data are available.

The left sketch in Fig. 8 shows, that the center of an 18 meter long igloo is 3 meters closer to the headwall than the center of a 24 meter long igloo.

To take this effect into consideration it is shown in Figure 9 that in this report all distances are measured from the center of each type of igloo, thus resulting in different scaled distances for different ground plans at equal charge weight.

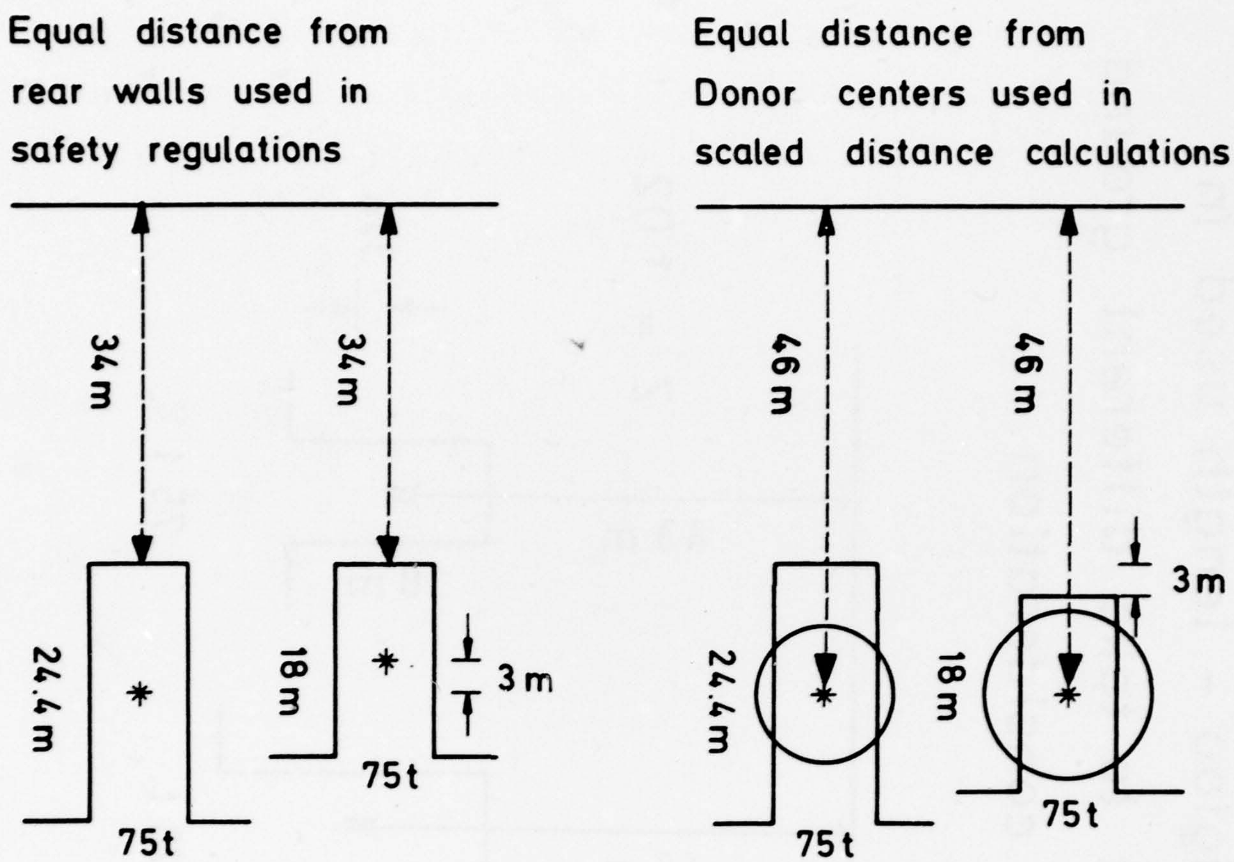
ESKIMO I	18 m × 7,6 m
ESKIMO III	24,4 m × 8 m
UK ESTC	20 m × 7,5 m
BRL	18,3 m × 7,6 m and 24,4 m × 8
NDCS	Standard Norwegian Igloo
SWISS	37 m × 12 m

Effect on Peak Overpressure

No data available. Differences in peak overpressure at quantity distance $D = 0{,}8 \cdot Q^{1/3}$ for 18 m and 24,4 m Igloos at ESKIMO and BRL tests.

Fig. 7

Variation of Donor Ground Plan



$$D = 0{,}8 \cdot Q^{1/3} \qquad R = 1{,}09 \cdot Q^{1/3}$$

Fig. 8 Variation of Igloo Ground Plans

Quantity distance from rear wall plus 1/2 igloo - length used in this report to take different ground plans into consideration.

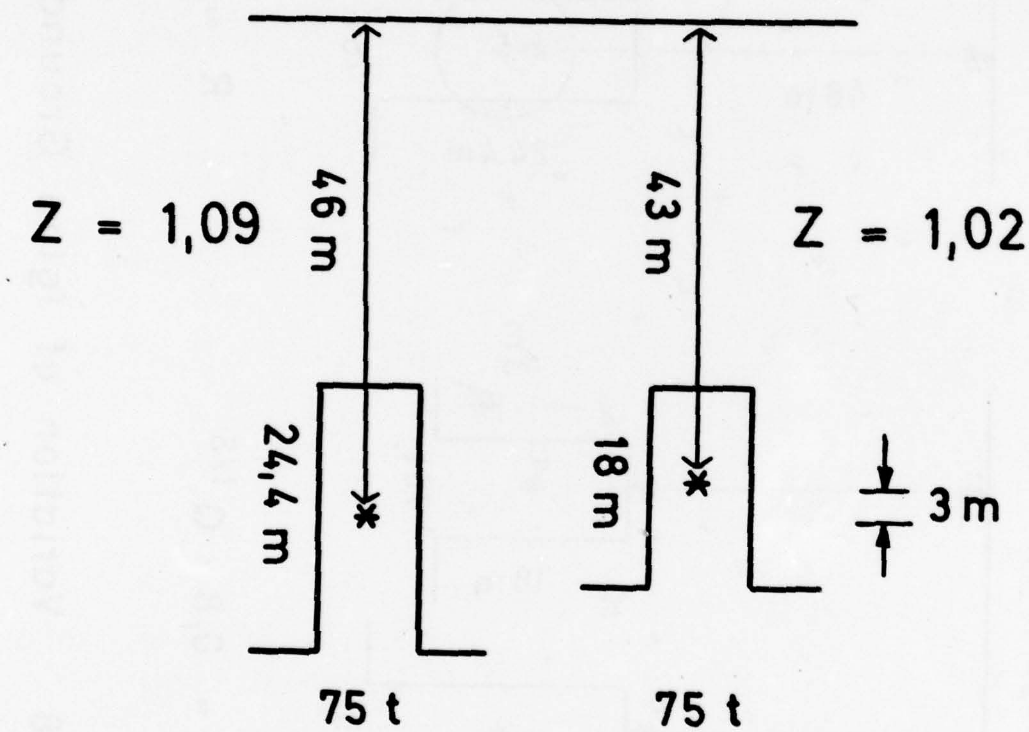


Fig. 9

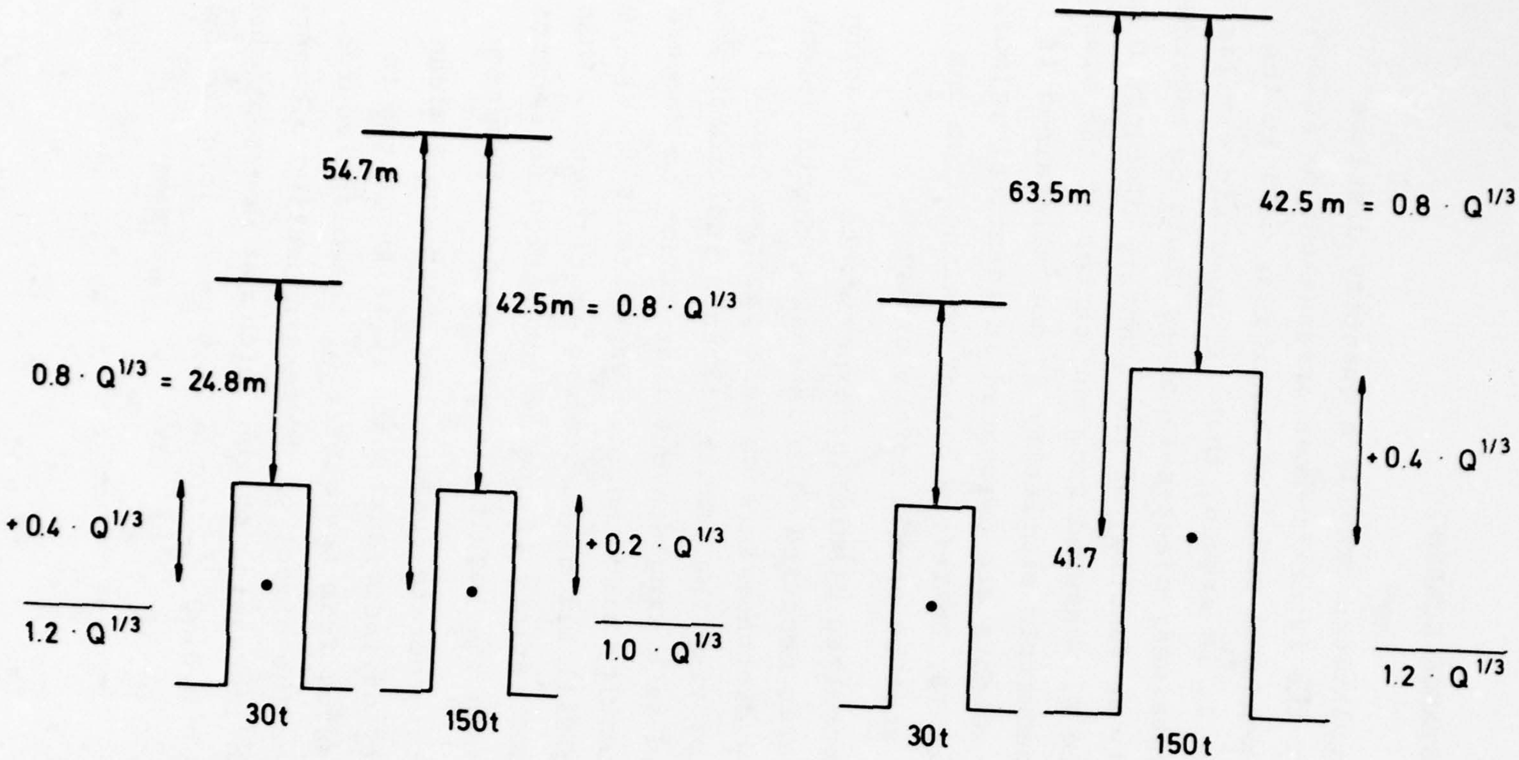
Variation of Igloo Ground Plans

VI. DISTANCE SCALING

Current safety regulations provide a quantity distance $D = 0.8.\ Q^{1/3}$ for the front-to-rear arrangement of igloos. The distance is measured from the donor rear wall to the acceptor headwall. It is argued, that if geometric similarity were strictly maintained, blast parameters could be regarded with equal validity as function of the quantity distance D as of scaled distance Z, measured from the center of the blast source. However geometric similarity is not maintained if different charge weights are detonated in identical igloos, as shown in Figure 10. Therefore direct scaling from one charge weight to another should not be expected.

As a result of geometric dissimilar experiments increasing peak overpressure is measured with incrasing charge weight at fixed quantity distance in each test program (Table 1). From this point of view the result for each individual shot will be presented as a single event that cannot be compared with any other result, since not two experiments in all igloo test programs fulfill all blast scaling requirements. This procedure will not satisfy if one is interested to reconcile differences between the results in various test programs.

For an attempt to generate scaling laws that would widen the applicability of individual tests it is suggested to measure all distances from the center of the blast source. Table 2 describes the effect of decreasing scaled distance $Z = {}^{R}/Q^{1/3}$ with increasing charge weight at constant quantity distance $D = 0.8.\ Q^{1/3}$ for a 24.4 meter long igloo.



Geometric dissimilar experiments:
Increasing peak overpressure
with increasing charge weight
at $D = 0.8 \cdot Q^{1/3}$

Geometric similar experiments:
Equal peak overpressure at $D = 0.8 \cdot Q^{1/3}$

Fig. 10 Ground Plan Similarity

Table 2

Quantity distance D and scaled distance Z for a 24.4 m igloo

Q in kg	$Q^{1/3}$	D in m	R in m	$D/Q^{1/3}$	$R/Q^{1/3}$
30,000	31.1	24.8	37.0	0.8	1.19
90,000	44.8	35.8	48.0	0.8	1.07
270,000	64.6	51.7	63.9	0.8	0.99

The Figure 11 describes the effect of using the scaled distance parameter instead of quantity distance. The side on peak overpressure at fixed quantity distance D = 0.8. $Q^{1/3}$ varies from 1.8 bar to 3.8 bar with different test arrangements and increases with increasing charge weight within single test programs. By using the scaled distance parameter do we notice decrasing peak overpressure with increasing scaled distance. This corresponds to what we know of a hemispherical surface burst. The decay of pressure from an igloo blast source is at a far slower rate than from an open charge, but with smaller peak pressure at equal scaled distance.

Even with scaled distance do we find different results with various test programs. As is seen from Figure 11 does the peak overpressure at equal scaled distances decrease with increasing arch thickness.

VII. ARCH AND COVER THICKNESS

Current safety regulations provide a standard 0.6 m sand cover for ammunition storage houses but do not take into consideration different arch thickness. The arch thickness varies in different test programs from 0.002 m of corrugated steel in ESKIMO III to 0.6 m of reinforced concrete in ESTC 1972, The arch material of

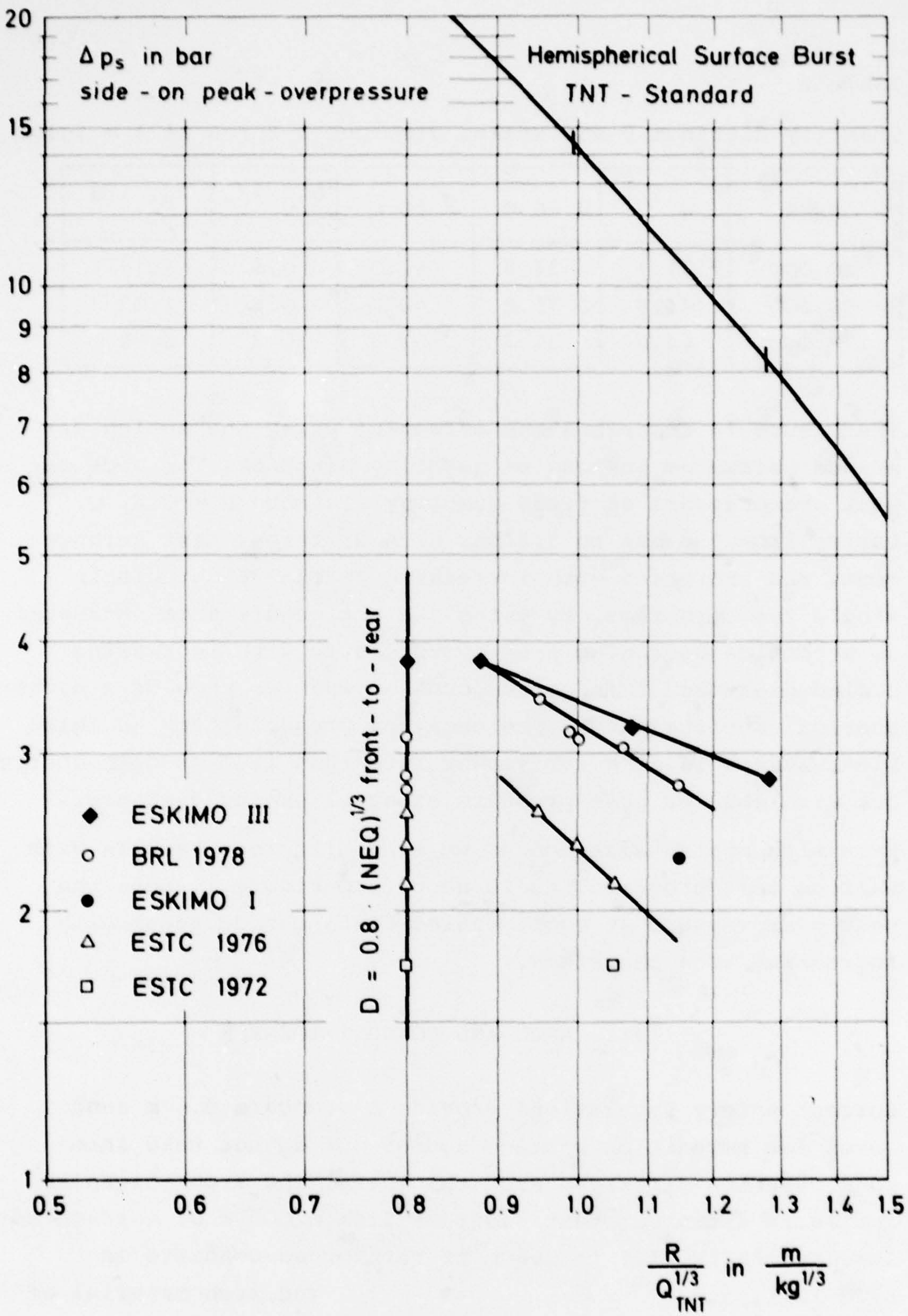


Fig. 11 Peak overpressure vs scaled distance

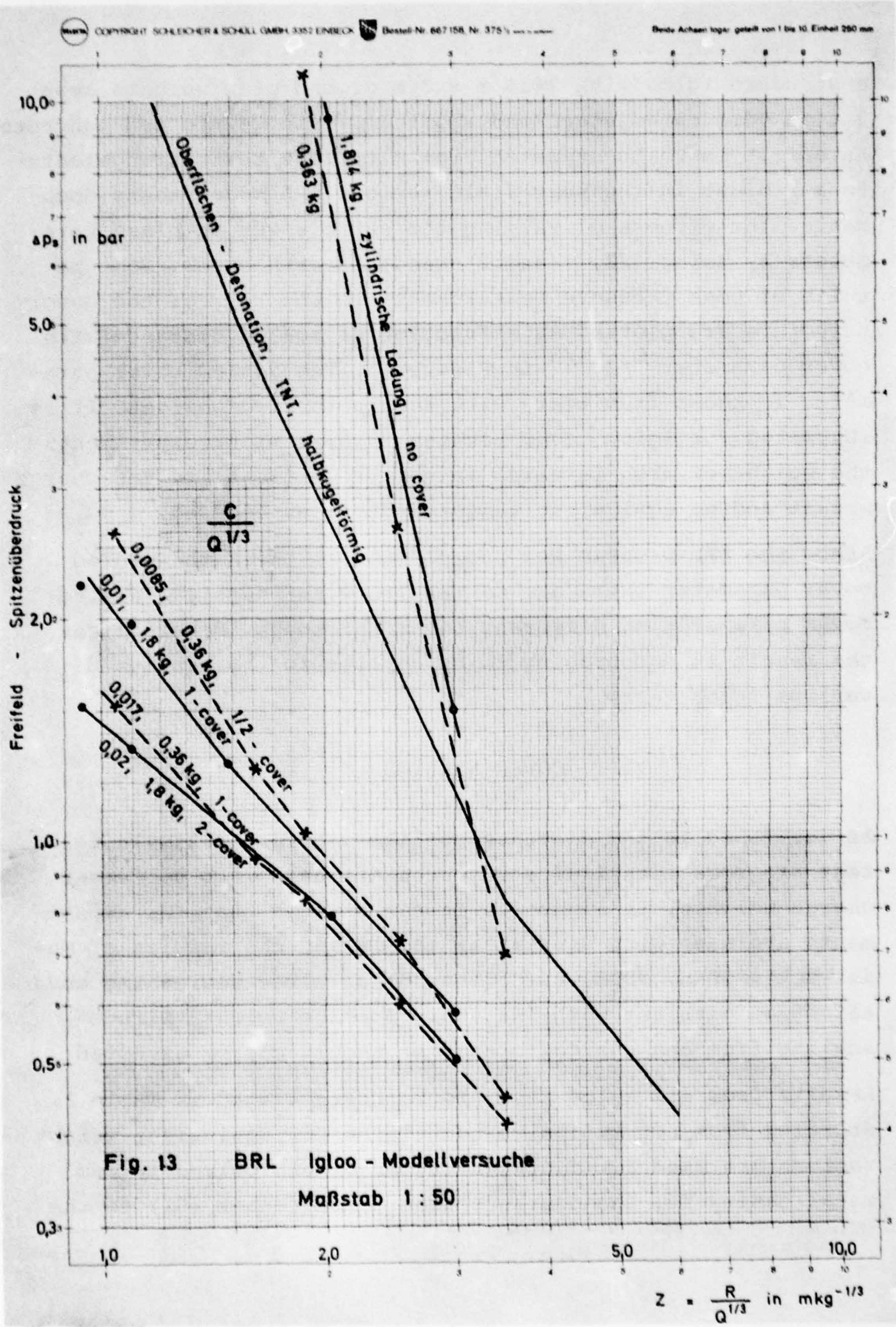
a standard igloo with 24.4 m x 8 m ground plan weights about 3 t in corrugated steel and about 300 t in reinforced concrete. An effect is to be expected frc different test arrangements to air blast in the near field region. BRL model tests documented the effects of varying the earth cover on blast parameters by using 1/2, 1 and 2 standard earth cover. Some results of peak pressure measurements to the rear of the donor structure are plotted as a function of scaled distance with cover parameter $^{C}/Q^{1/3}$ in Figure 13. The scaled cover parameter is known from tests with shallow buried charges. It is suggested for igloo cover because in dissimilar experiments the weight of arch material is not proportional to the charge weight and no equivalent weight factor can be used.

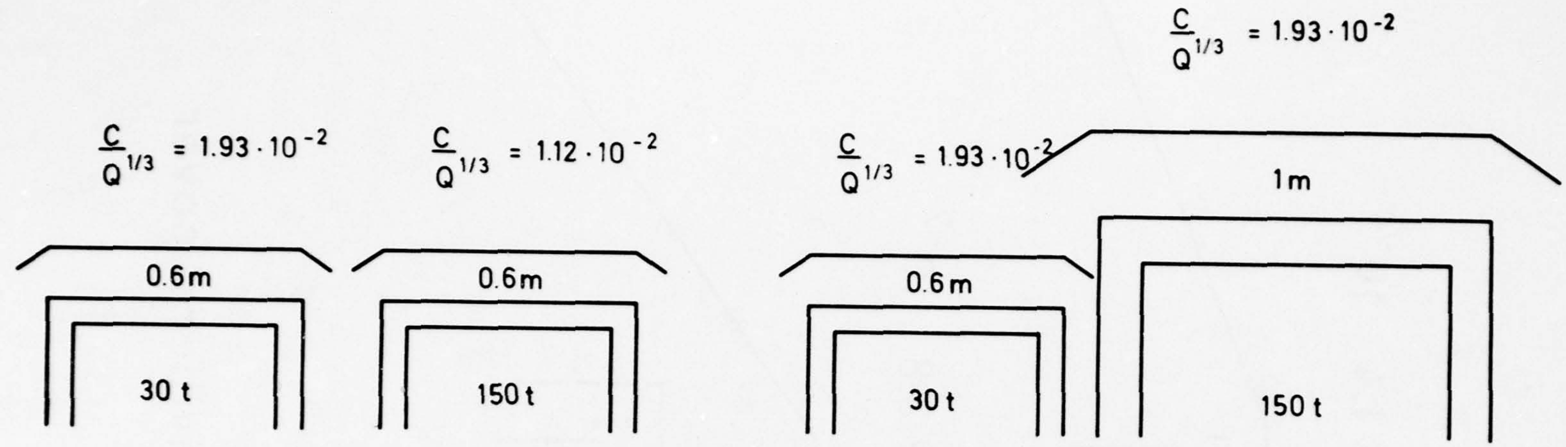
Since the BRL program was not planned to check the scaled cover parameter there are no results with identical scaled cover parameter at different cover thickness. Nevertheless the result is encouraging to be applied to the results of various igloo tests.

VIII. COVER SCALING

As described in the distance scaling section in single igloo test programs identical structures are used with different charge weights. In Figure 14 it can be seen that the experiments are made with dissimilar models and the results of model tests (BRL, NDCS, ESTC) show clearly the decreasing cover effect on airblast with increasing charge weight. Direct scaling from one charge to another should not be expected.

Results from six igloo test programs are listed in Table 3. Starting from net explosive quantities NEQ, equivalent weight factors are used for different types of explosives fe and metal casing fc. The distance from donor center (GZ) to the


COPYRIGHT SCHLEICHER & SCHÜLL GMBH 3352 EINBECK
Beide Achsen logar. geteilt von 1 bis 10. Einheit 250 mm
Oberflächen - Detonation, TNT, halbkugelförmig
1,814 kg, zylindrische Ladung, no cover
0,363 kg
0,0085, 0,36 kg, 1/2 - cover
0,01, 1,8 kg, 1 - cover
0,017, 0,36 kg, 1-cover
0,02, 1,8 kg, 2-cover
$\frac{C}{Q^{1/3}}$
Δp_s in bar
Freifeld - Spitzenüberdruck
Fig. 13 BRL Igloo - Modellversuche
Maßstab 1 : 50
$Z = \frac{R}{Q^{1/3}}$ in $mkg^{-1/3}$



Dissimilar experiments:
Increasing peak overpressure with increasing charge weight at equal scaled distance

Similar experiments:
Equal peak overpressure at equal scaled distance

Fig. 14 Cover Similarity

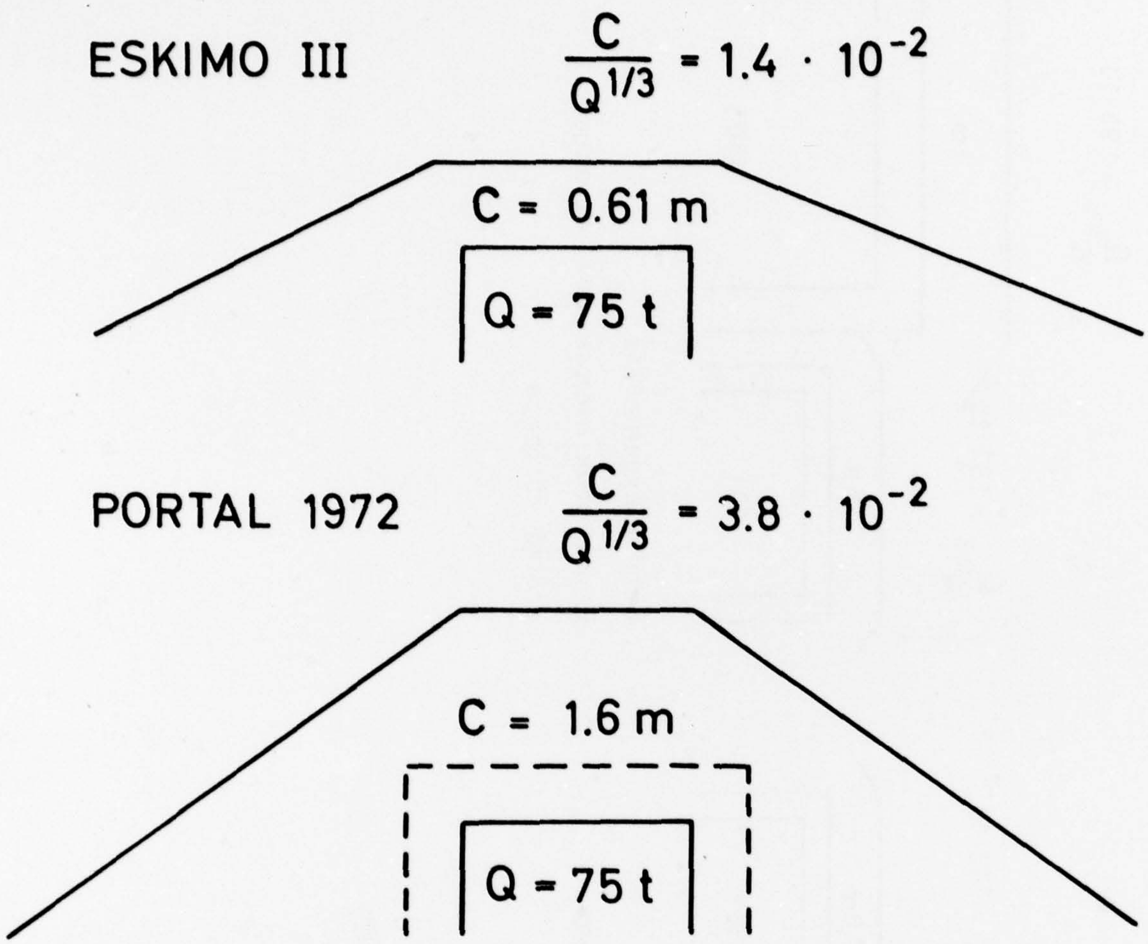


Fig. 15

Variation of sand - equivalent cover

measure points is calculated and scaled by the cube root of the equivalent TNT charge Q_{TNT}. Only results from measurements at scaled distances $Z \sim 1$ are taken into consideration.

The material of the arch is considered as additional cover, the equivalent thickness of sand added being in the ratio of the density of arch material to that of the sand fill. The assumption is made that inertia rather than strength effects dominate the generation of air blast. Cover thickness ranging from C = 0.61 m to C = 1.6 m is listed and scaled by the cube root of the effectiv TNT charge weight Q_{TNT} in the same way as scaled distance , (Figure 15).

In some tests pressure measurements were taken side-on and in other tests regular reflected at the bottom of the acceptor headwall. The results are listed together with the gage numbers.

The regular reflected peak overpressures are plotted as a function of scaled cover in Figure 16. As model experiments at BRL have shown that the suppression of blast by the cover varies with distance only measurements near the scaled distance Z = 1 are taken into consideration ($0.95 \leq Z \leq 1.05$). For example there is no measurepoint at Z = 1 in the ESKIMO I test.

It is seen as a result that the pressure measurements from five different test programs fit to one curve, which describes the overpressure decrease with increasing scaled cover at one fixed scaled distance. The data base is too small at the moment to plot curves for other scaled distances than Z = 1.

IX. RESULTS

A new format of data presentation for the results of blast measurements is suggested in order to reconcile differences between results in various igloo test programs and to widen the appli-

Table 3 Headwall Loading on Acceptor Frontwall to the Rear of a Donor Scaled Distance about 1

TEST	NEQ in kg	f_e	f_c	Q_{TNT} in kg	$Q^{1/3}_{TNT}$	R in m from GZ	$R/Q^{1/3}_{TNT}$ Z	C in m sand equ	$C/Q^{1/3}_{TNT}$ 10^{-2}	Δp in bar	Δp in bar	gage no
ESK,I	90,700	1	0.64	58,048	38.7	44.2	1.14	0.64	1.65	2.27	–	S.r.g.
						44.2	1.14			2.27	–	S.l.g.
						44.8	1.16			-	5.2	S.r.w.
						44.8	1.16			-	5.0	S.l.w.
ESK,III	158,500	1.13	0.73	134,903	51.3	44.5	0.87	0.61	1.19	3.8	-	106 E
						55.2	1.08			3.2	-	141 E
						65.9	1.28			2.8	-	176 E
ESTC	64,000	1	1	64,000	40	42	1.05	1.6	4.0	-	5.6	bottom
1972										-	5.6	"
ESTC	64,000	1	1	64,000	40	42	1.05	1.1	2.75	-	7.3	18
1976						.37	0.92			3.4	-	17
	125,000	1	1	125,000	50	45	0.9	1.1	2.2	4.4	-	17
						50	1.0			-	8.4	18
	216,000	1	1	216,000	60	53	0.88	1.1	1.83	6.7	-	17
						58	0.97			-	9.4	
NDCS	70,000	1	1	70,000	41.2	43	1.04	0.75	1.82	-	9	
1976										-	10	
	130,000	1	1	130,000	50.6	50.5	1.0	0.75	1.38	-	14.5	
											15.5	
	513,000	1	1	513,000	80	74	0.92	0.75	0.94	-	15.0	
											17.0	
BRL	44,583	1.05	1	46,812	36	41	1.14	0.75	2.08	-	10.2	C 1
1978	133,290			139,954	52	53.7	1.03		1.44	-	10.4	C 1
	224,000			235,200	62	61.6	0.99		1.21	-	12.1	C 1

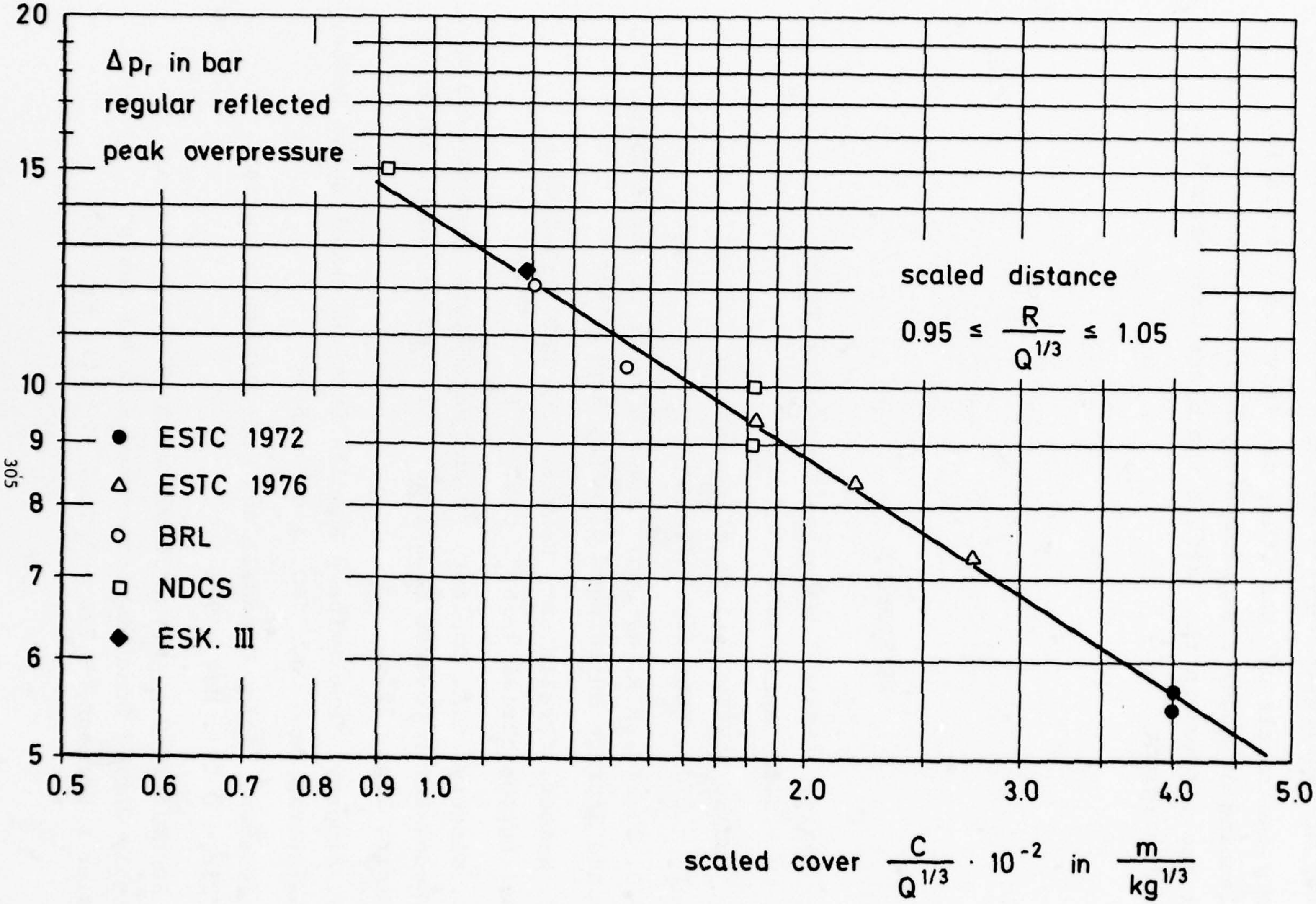


Fig. 16 Peak pressure at Acceptor - Frontwall

cability of individual experiments by blast scaling methods.

Possibly the result of this study can serve as a basis for the planning of model tests for studying in a systematic manner the parameters that affect the blast wave around a detonating igloo.

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Blast Parameters from Munition Storage Magazine Model Studies

Charles N. Kingery

ABSTRACT

This paper is a review of published, unpublished, and planned studies of the blast parameters generated from accidental explosions in earth covered munition storage magazines using 1/50th and 1/30th scaled models. Free field blast propagation from donor models as well as the blast loading on acceptor models are described and compared with full-scale results where available. Just completed current studies are included and planned future work is described.

I. INTRODUCTION

A. Background

The blast generated from accidental explosions in munition storage magazines is the primary mechanism for damage to other storage magazines.

This paper will review published work[1] covering free-field blast parameters from explosions in scaled model earth covered munition storage magazines and the ESKIMO V[2] model donor tests. Also presented are current unpublished studies designed to determine the blast loading on model acceptor magazines from explosions in model donor magazines when located at the safe separation distances. Included in this paper are also the results from the blast loading on structures placed in-line front and rear of the donor versus off-line placement.

B. Objectives

The primary objective of this paper is to review past work, present results from current work, and discuss plans for future work related to free-field blast parameters and blast loading on munition storage magazines using scaled models.

II. DESCRIPTION OF PROJECTS AND RESULTS

A. Effect of Earth Cover on Blast Parameters

1. Objective. The objective of this project was to determine the effect of different thicknesses of earth cover over a munition storage magazine on the propagation of blast parameters from an accidental explosion.

2. Test Procedure. A 1/50 scale standard munition storage magazine modeled for this series of tests is shown in Figure 1. The dimensions associated with the letters in Figure 1 are listed in Table I which includes the full-size and model structure. The internal portion of the 1/50 scale model donor magazine is shown in Figure 2 while the external earth covered model is shown in Figure 3. The instrumentation system is shown in Figure 4. Pressure transducers were located to the front, side, and rear of the donor magazine, starting at the safe separation distance of $0.5Q^{1/3}$ to the side, and $0.8Q^{1/3}$ to the front and rear, where Q is the weight of the explosive in kilograms.

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[1] C. Kingery, G. Coulter, and G. Watson, "Blast Parameters from Explosions in Model Earth Covered Magazines," BRL MR-2680, September 1976.
[2] Charles Kingery, "Blast Loading on Model Earth Covered Magazines," ARBRL-TR-02092, September 1978.

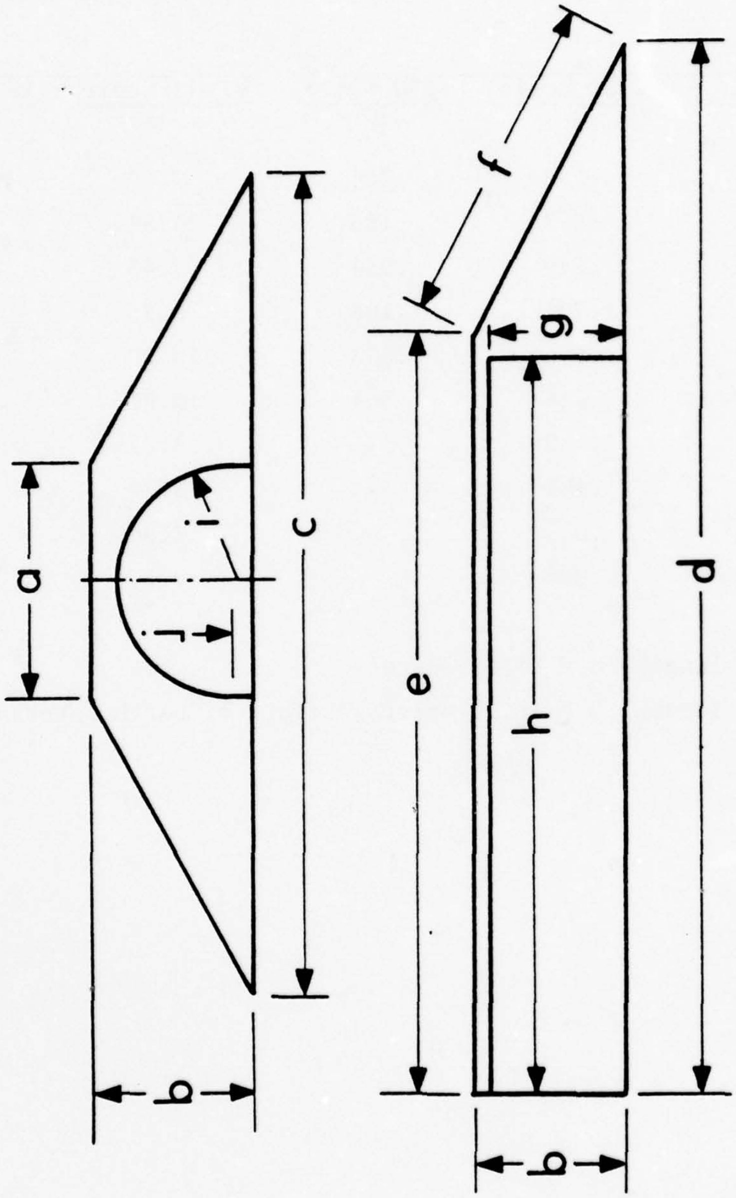

Figure 1. Standard Munition Storage Magazine

Table I. Full Scale and Model Dimensions

	1			2	
	Full Scale	1/50 Scale	1/30 Scale	Full Scale	1/50 Scale
	m	m	m	m	m
a	7.92	.158	.264	7.92	.158
b	4.88	.098	.163	4.88	.098
c	27.43	.549	.914	27.43	.549
d	35.05	.701	1.168	28.96	.579
e	25.30	.506	.843	19.20	.384
f	10.91	.218	.364	10.91	.218
g	4.27	.085	-	4.27	.085
h	24.38	.488	-	18.29	.366
i	3.96	.079	-	3.96	.079
j	0.30	.006	-	0.30	.006

1 - Interior length, h = 24.38 metres.

2 - Interior length, h = 18.29 metres, Effect of Earth Cover Study.

Figure 2. Internal Portion of Model Donor Magazine

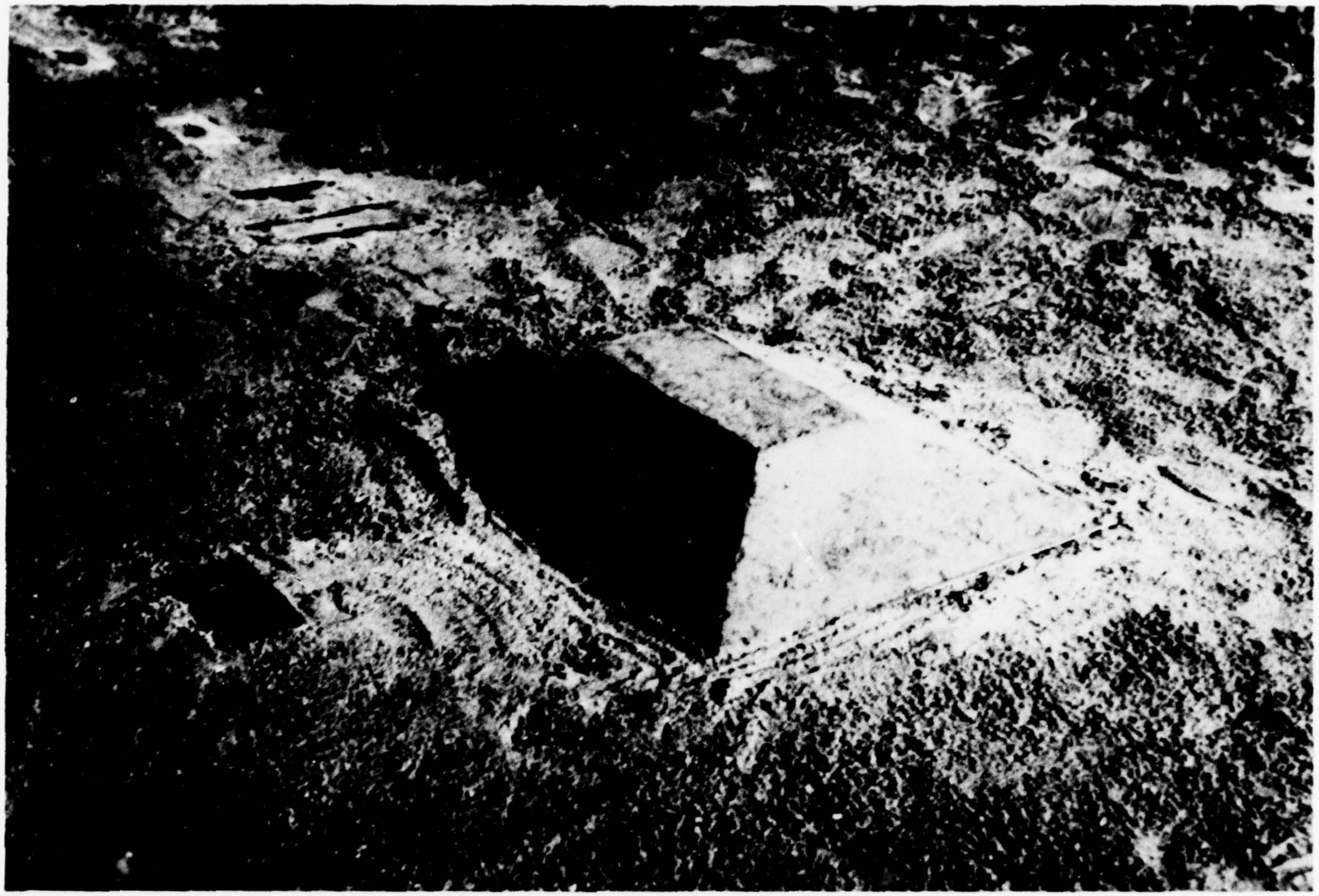

Figure 3. External View of Model Earth Covered Donor Magazine

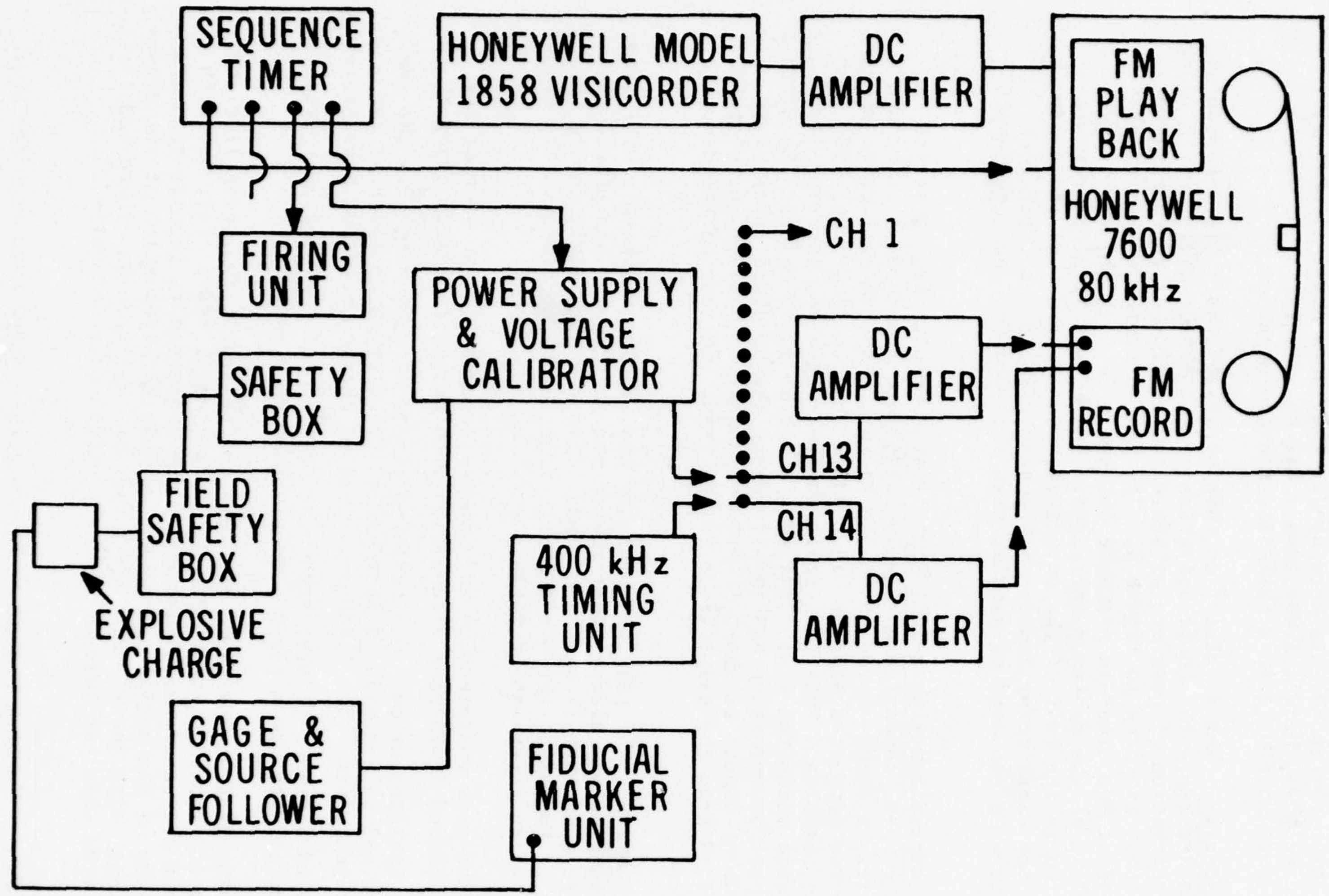

Figure 4. Instrumentation System

Three charge weights were used. They were hemi-cylindrical pentolite weighing 0.363, 1.088, and 1.814 kg, simulating 45 360, 136 000, and 226 800 kg in a full-size storage magazine.

3. Results. The results from this series of tests are reported in detail in Reference 1. An illustration of the effect of the earth cover on the propagation of peak overpressure to the side of the donor (90 degree line), is given in Figure 5. The peak overpressure is greatly attenuated at the close-in distance but the effect of the earth cover becomes less as the distance increases. There is a similar pressure attenuation to the rear of the structure. To the front of the donor magazine the earth cover causes an opposite effect; i.e., the peak overpressure is enhanced or greater than recorded for uncovered explosive.

4. Correlation with a Full-Scale Test. Results from a series of full-scale tests conducted during 1962-1963 are reported in Reference 3. In test six, a donor charge of 45 360 kg in a standard 18.3 metre storage magazine was detonated and the blast parameters to the front, side, and rear were measured. This full-scale charge weight and interior structure volume ratio match the 0.363 kg fired in a 1/50 scale model. The correlation of peak overpressure and impulse along the 90 degree blast line (from side of donor) is shown in Figures 6 and 7. Similar correlation was obtained from the blast lines to the front and rear of the donor structures.

5. Summary. The peak overpressure and impulse recorded to the front of the magazine was always greater when the earth cover was placed over the charge than when it was uncovered. This was apparently due to the earth walls focussing the blast energy from the three sides to the front headwall where there was no earth cover.

The peak overpressure and impulse recorded to the side of the magazine showed increasing attenuation with increasing earth cover at the close-in stations or out to a scaled distance of 2.86 $m/kg^{1/3}$. The small charge, 0.363 kg, recorded a decreasing effect of earth cover as the distance increased. The 1.088 and 1.814 kg charges recorded a crossover at a scaled distance greater than 3.88 $m/kg^{1/3}$ and the peak overpressures were greater with the magazine covered than when uncovered.

The peak overpressure recorded to the rear (180 degree line) of the magazine showed a large attenuation at the close-in stations, with the effect decreasing with distance. The overpressure impulse recorded to the rear of the magazine also showed a large attenuation at the close-in stations, with the effect decreasing with distance but there was little change noted when the thickness of the earth cover was varied.

[3] *A. R. Sound, "Summary Report of Earth-Covered Steel-Arch Magazine Tests," NOTS-TP 3843, July 1965.*

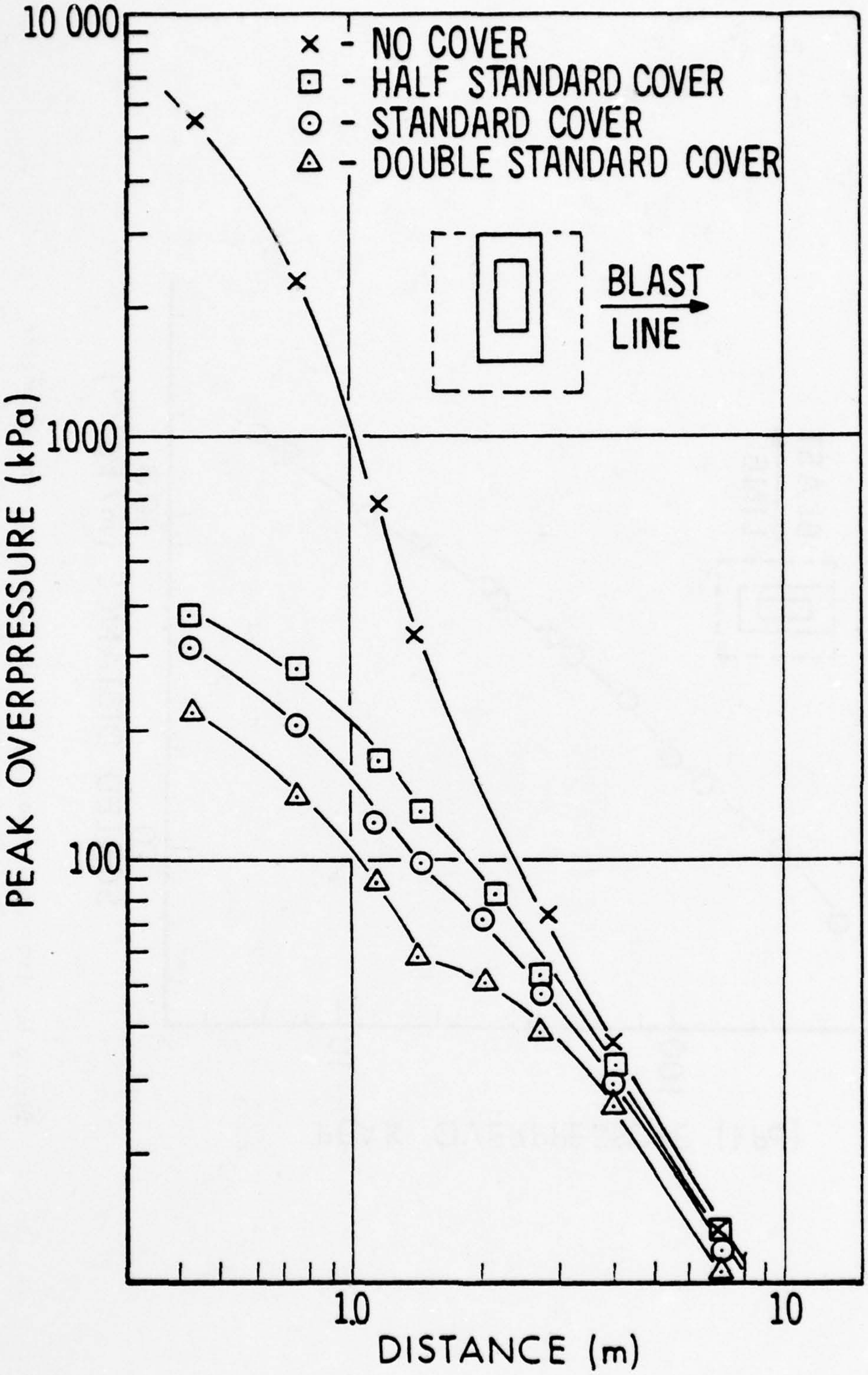

Figure 5. Pressure versus Distance Along the 90 Degree Line as a Function of Earth Cover for a 0.363 kg Charge

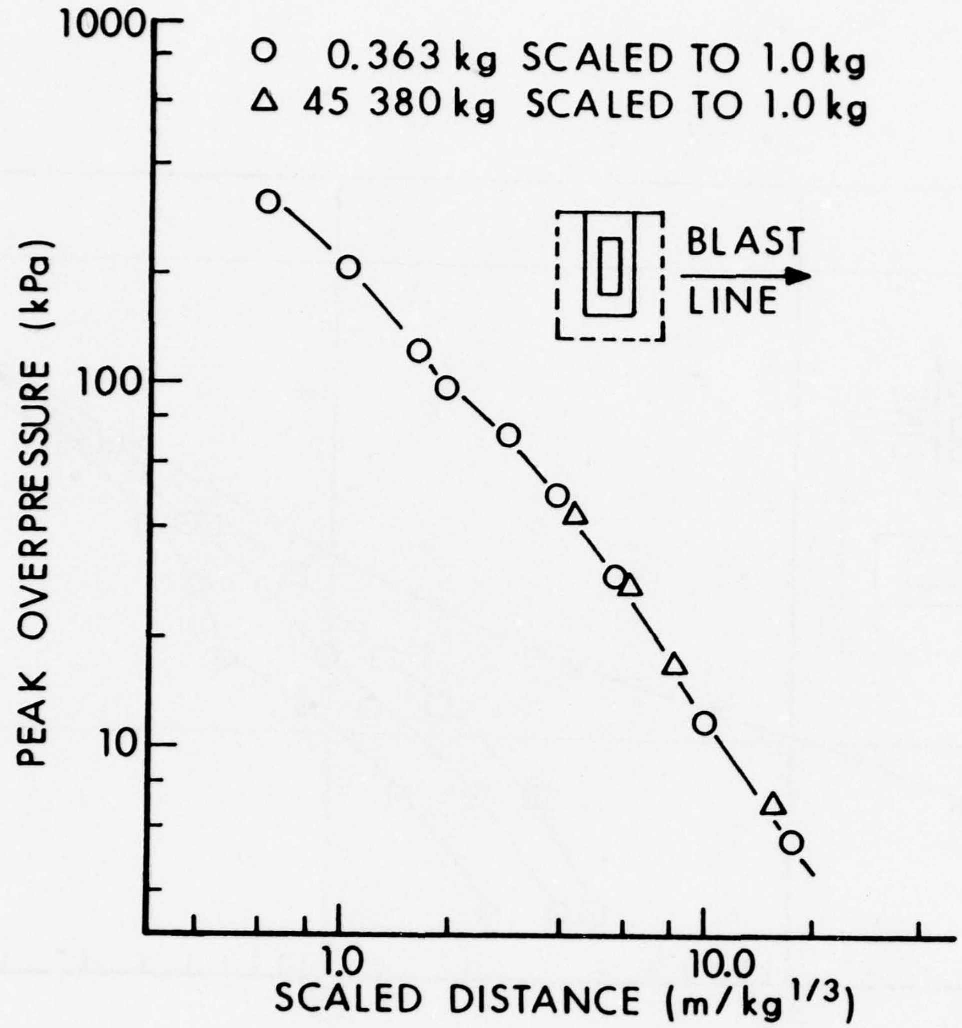

Figure 6. Pressure versus Scaled Distance Along the 90 Degree Line from a Full-Size Magazine and a 1/50 Scaled Model

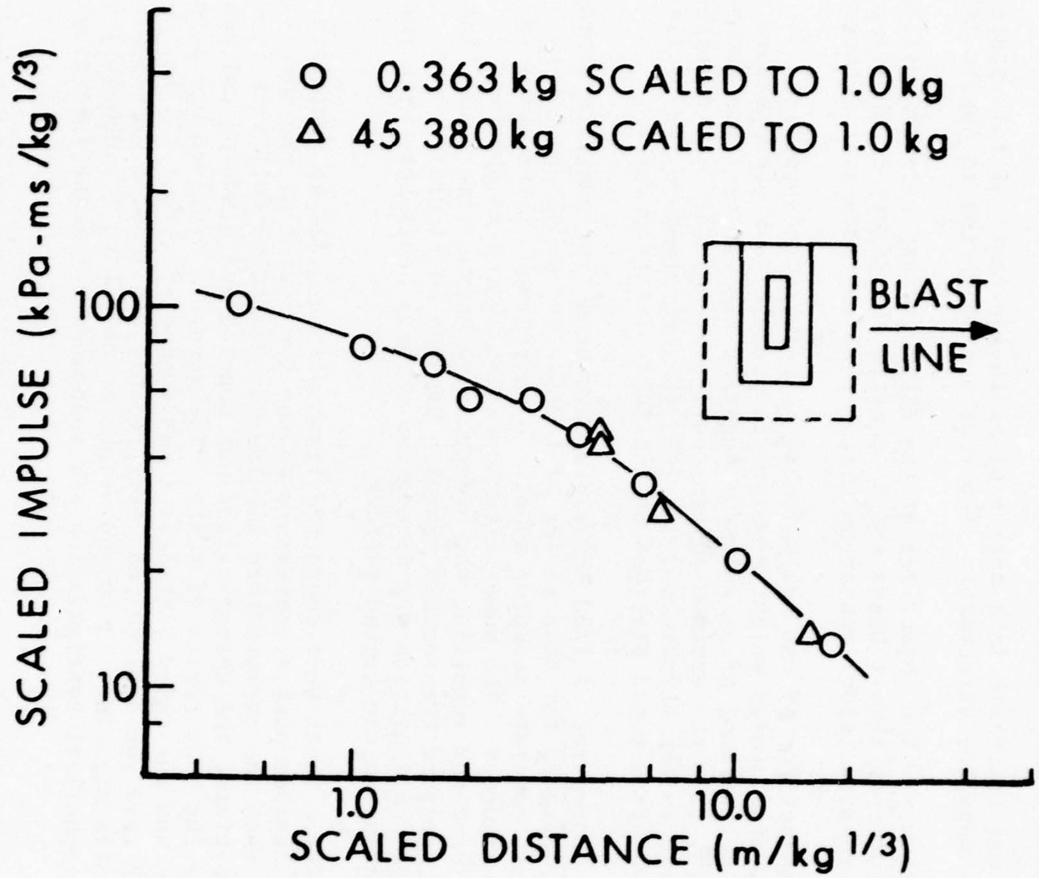

Figure 7. Scaled Impulse versus Scaled Distance Along the 90 Degree Line from a Full-Size Magazine and a 1/50 Scaled Model

In summary, it can be stated that the results of this series of tests have established many trends, and the effects of varying the earth cover on blast parameters to the front, side, and rear of the structure have been documented and correlated with results from a full scale test.

B. ESKIMO V Donor Simulation Tests

ESKIMO V was the fifth in a series of explosion tests of full-scale earth-covered magazine structures. The test was conducted in August 1977.

1. Objectives. The objectives of the ESKIMO V test were to justify eliminating concrete thrust beams and to confirm the safety of applying current side-to-side igloo separation distance to concrete-arch igloos.

The objectives of the scaled model tests were to establish (1) the uncovered charge weight required to produce peak overpressure and impulses on the roof of an acceptor magazine similar to those recorded on ESKIMO III[4], (2) the optimum charge configuration, (3) the distance from the charge to the structures, and (4) the overpressure versus time to be expected at selected stations on the full-size structure.

2. Test Procedure. A 1/30 scale standard arch type munition storage magazine was designed for this series of tests. The model was a non-responding cast concrete acceptor model. A photograph of the model is presented in Figure 8. The same instrumentation system as shown in Figure 4 was used for recording the overpressure versus time data. Locations of the pressure transducers can also be seen in Figure 8. The optimum charge configuration was determined to be a hemisphere with the flat side resting on the ground surface.

3. Results. Tests were conducted first with a 0.454 kg pentolite charge. The desired peak overpressure on the top center of the model was recorded but when the overpressure impulse was scaled to full size it was too low. Therefore, the charge weight was doubled and 0.908 kg charges were used for the next series of tests. The recorded overpressure impulse was still low and the third test series was conducted with 1.135 kg charges which gave the desired peak overpressure and impulse when scaled to the full size magazine. A charge weight of 34 000 kg (75 000 lbs) of TNT in a hemispherical configuration was recommended for the full-size test.

A comparison of the results obtained from the model scaled to full-size and the results from ESKIMO III are presented in Figure 9. Good correlation was achieved across the roof of the structure.

[4] *F. H. Weals, "ESKIMO III Magazine Separation Tests," Naval Weapon Center Report NWC-TP 5771, February 1976.*

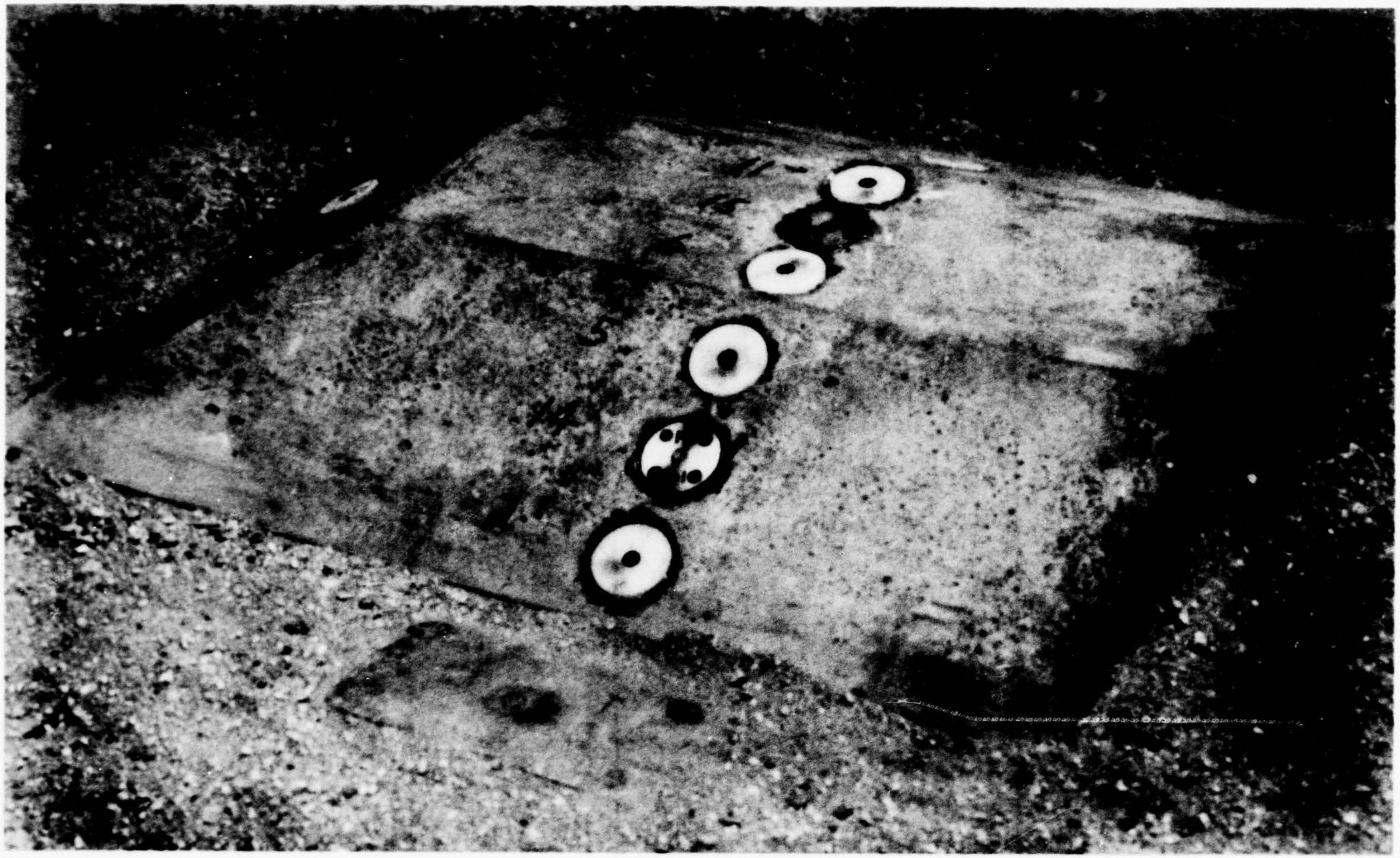

Figure 8. ESKIMO V Model Acceptor Magazine

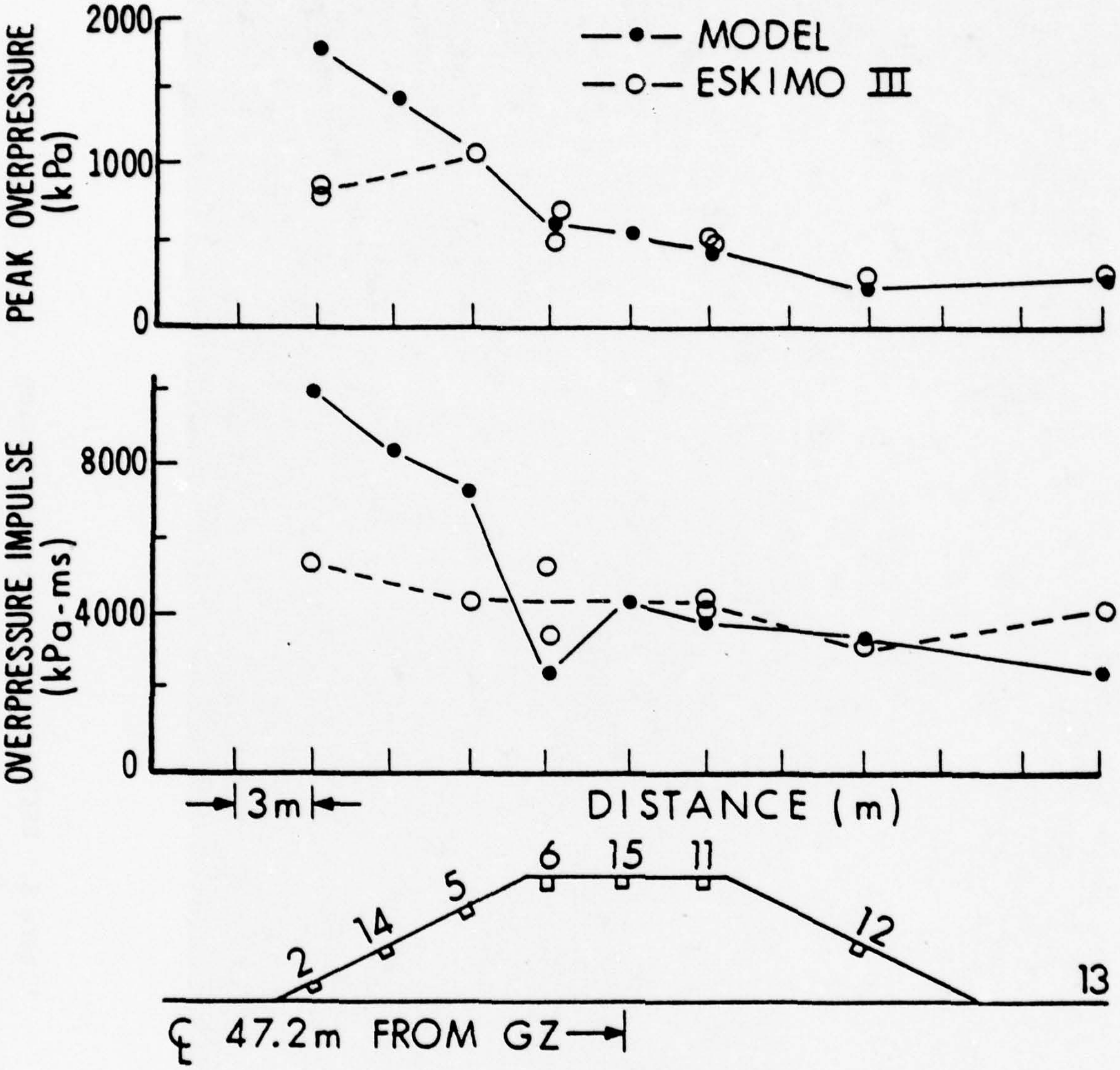

Figure 9. Comparison of Donor Simulation with ESKIMO III

4. Correlation with Full-Scale Test. The full-scale test, ESKIMO V, was conducted in August 1977 and the comparison of the model predictions with the recorded results are shown in Figure 10. Two full-size structures were exposed on the field test and selected pressure stations were duplicated giving two data points in Figure 10. The high value of peak overpressure and impulse recorded at Station 6 and the low value of impulse at Station 14 are suspect and should be ignored. The final field test report has not been published, therefore, the comparisons were made with preliminary results which may change in the published report.

5. Conclusions. Two conclusions may be drawn from the results from the model and full-scale tests. First, scaled models and high explosive charges can be used to design full-scale tests and second, smaller uncovered charges can be used to simulate blast loading from much larger charges placed in donor magazines.

C. Blast Loading on Model Acceptor Magazines

The propagation of blast parameters to the front, sides, and rear of a model donor magazine and the blast loading on model acceptor magazines from an uncovered charge have been presented. The results from a series of tests using a 1/50th scale model donor magazine and three acceptor magazines to determine the blast loading will now be discussed.

1. Objective. The objective of this series of tests was to determine the blast loading on model acceptor magazines, when placed to the front, side, and rear of a donor magazine, at the established safe-separation distance, for three different explosive yields.

2. Test Procedure. The dimensions of the donor and acceptor models are shown in Figure 1 and Table I. The instrumentation system is shown in Figure 4. The mean values of the three charge weights were 0.357, 1.066, and 1.792 kg of pentolite in a hemicylindrical configuration. These charge weights represent 44 625, 133 250, and 224 000 kg of explosive in a full size magazine. The test layout and gauge positions are shown in Figure 11. A photograph of the donor and acceptor models placed in the test area is presented in Figure 12. Three charges were fired for a specific charge weight and then the test configuration was altered to meet the new separation distances.

3. Results. A detailed analysis of the overpressure and impulse versus time recorded at the pressure gauge stations will be published in a BRL Report. In this paper, emphasis will be given to the blast loading on the top surface and headwalls of the structures.

The mean values of overpressure and impulse recorded on Structure A (to the front of the donor) are listed in Table II. The records obtained at Stations A-4 and A-6 are presented in Figure 13 for the 1.792 kg charge representing a full size storage of 224 000 kg (494 000 lbs) of explosive. It should be noted here that the peak overpressure recorded at Station A-4 is greater than A-6 (1410 versus 1000 kPa mean values).

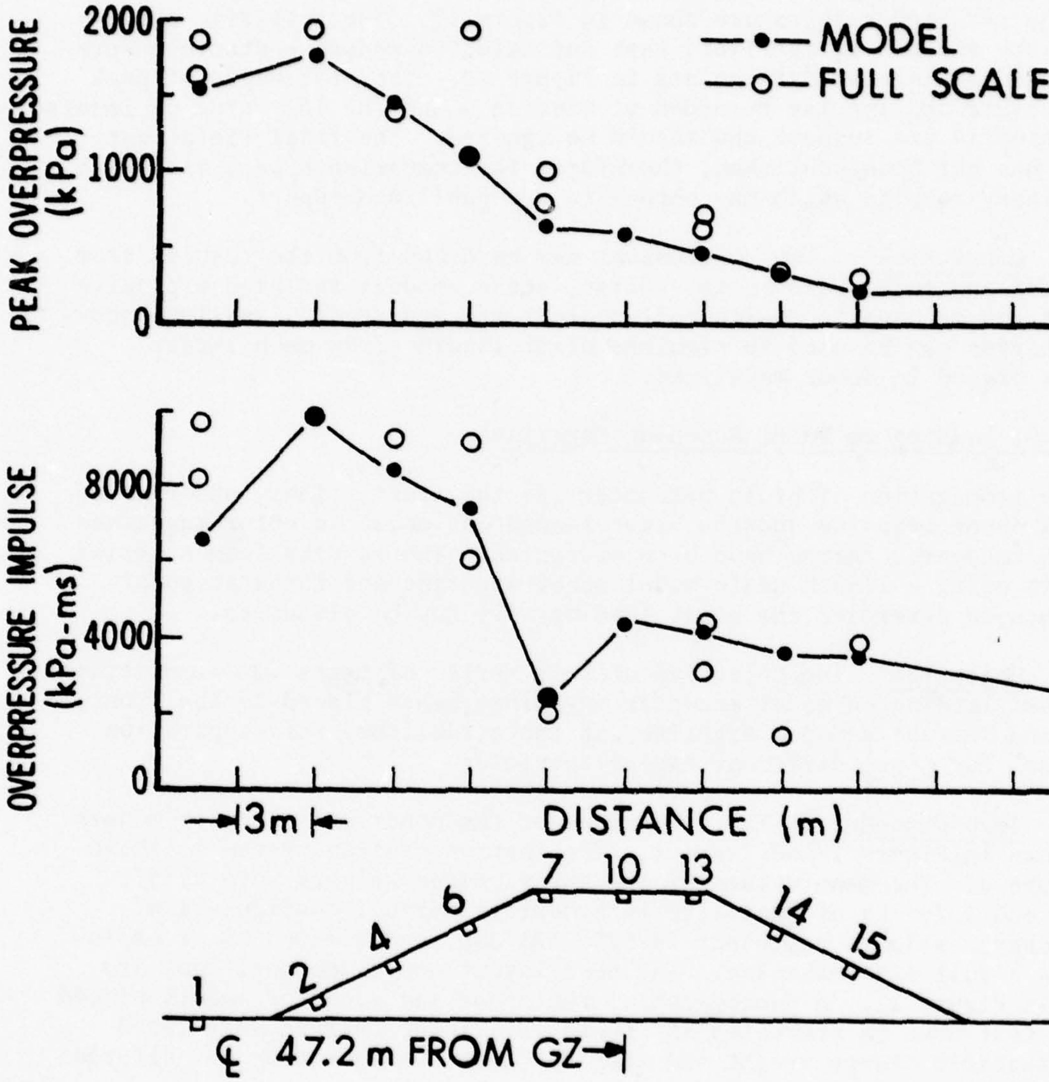

Figure 10. Comparison of Model Predictions with Full-Scale Results

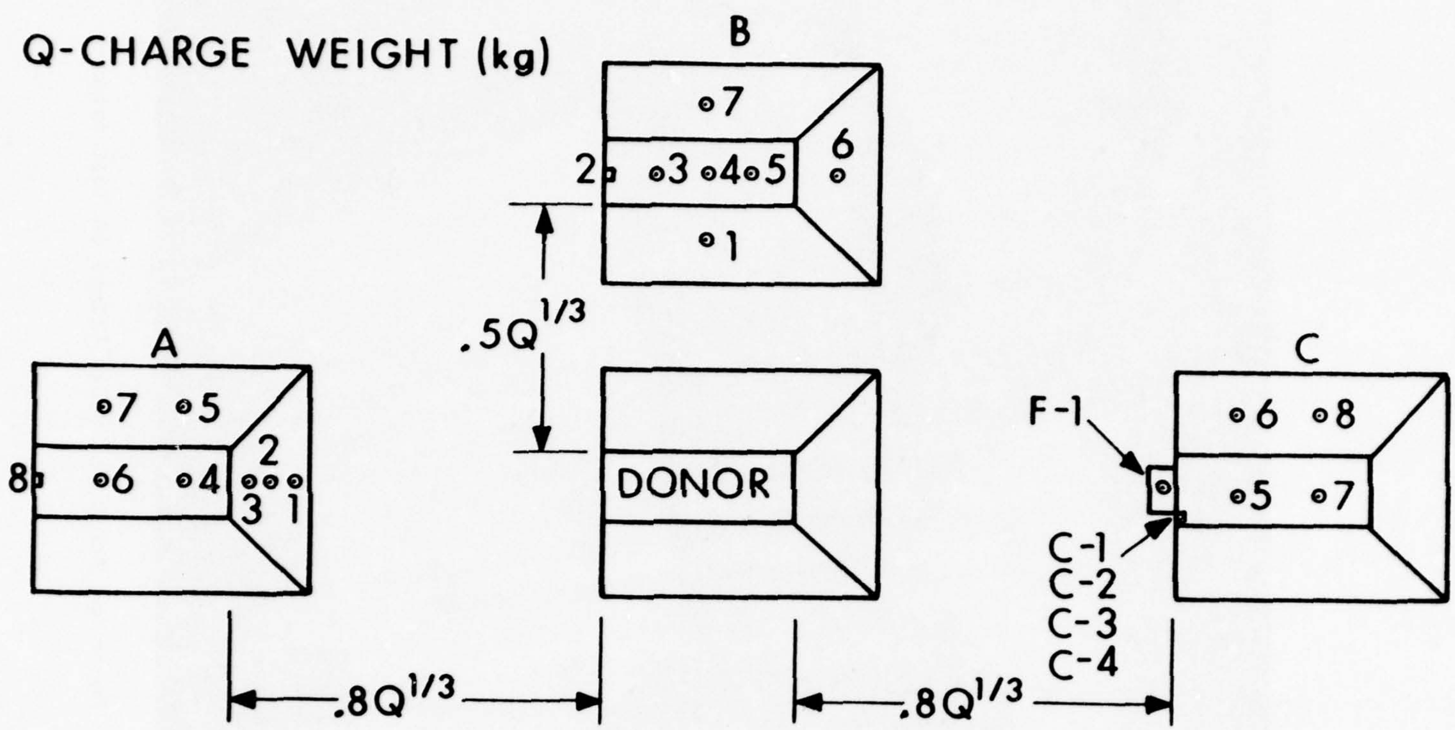

Figure 11. Test Layout

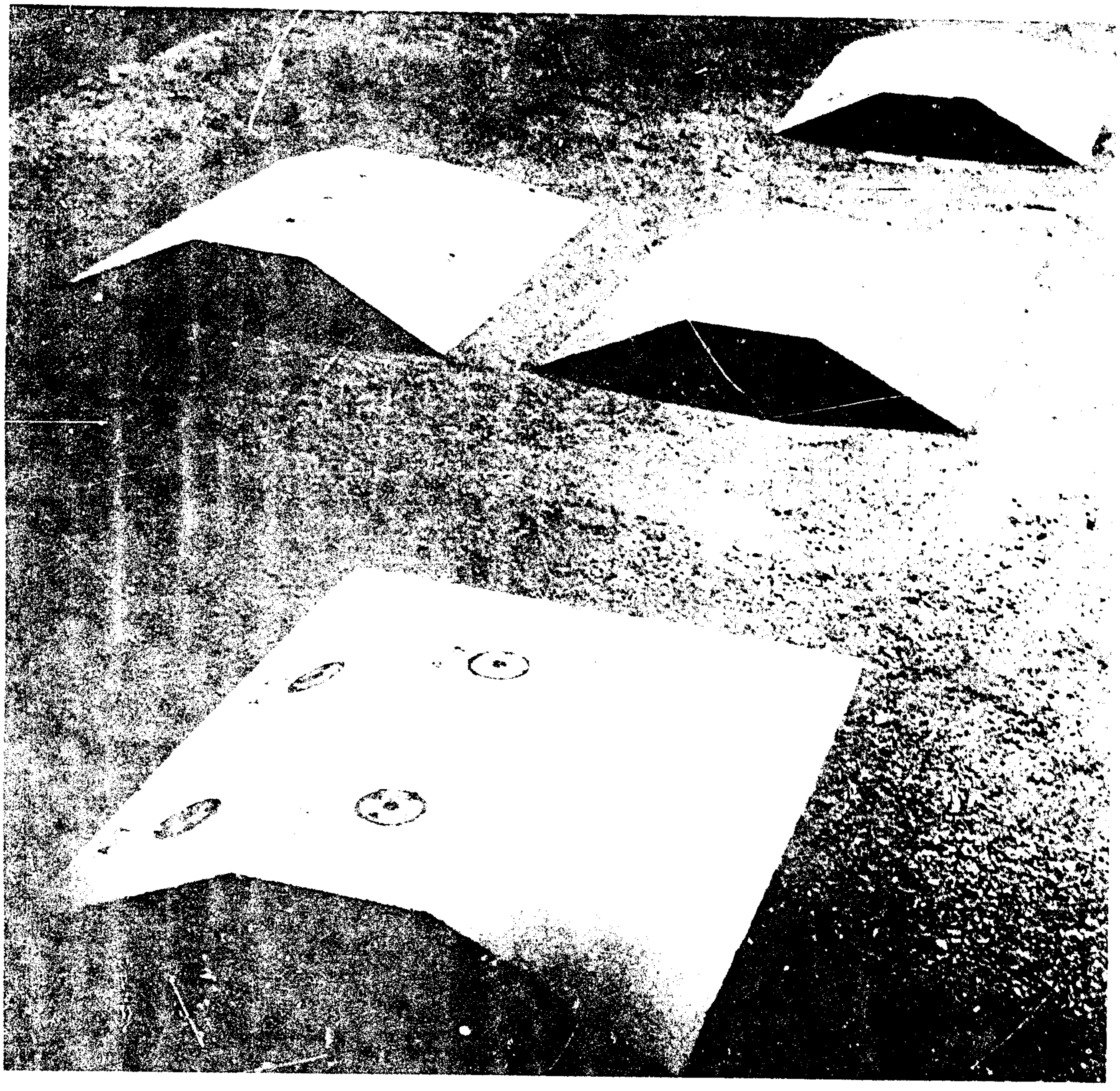

Figure 12. Donor and Acceptor Models Placed in Test Area

Table II. Blast Parameters Loading Structure A

Charge Weight	Gauge Station	Distance from GZ	Arrival Time	Peak Overpressure			Positive Impulse			Duration Positive Pressure
kg		m	ms	bar	kPa	psi	bar-ms	kPa-ms	psi-msec	ms
0.357	A-1	0.630	0.34	33.0	3300	479	-	-	-	-
	A-2	0.697	0.39	20.2	2020	293	-	-	-	-
	A-3	0.751	0.42	17.5	1750	254	-	-	-	-
	A-4	0.920	0.59	7.26	726	105	0.790	79.0	11.4	0.44
	A-5	0.937	0.65	7.04	704	102	0.933	93.3	13.5	0.81
	A-6	1.174	0.91	3.46	346	50	0.546	54.6	7.9	0.63
	A-7	1.187	0.97	3.92	392	57	0.704	70.4	10.2	0.71
	A-8	1.300	1.19	.57/.76	57/76	8.3/11	0.524	52.4	7.6	1.51
1.066	A-1	0.875	0.38	36.3	3630	526	-	-	-	-
	A-2	0.942	0.43	24.2	2420	351	-	-	-	-
	A-3	0.996	0.44	21.1	2110	306	-	-	-	-
	A-4	1.166	0.60	11.5	1150	167	1.310	131.0	19.0	0.48
	A-5	1.178	0.61	10.5	1050	152	1.674	167.4	24.3	0.89
	A-6	1.419	0.85	6.62	662	96	1.554	155.4	22.5	0.97
	A-7	1.430	0.88	6.02	602	87	2.059	205.9	29.9	1.52
	A-8	1.545	1.10	1.18/2.74	118/274	17/40	1.788	178.8	25.9	1.97
1.792	A-1	1.035	0.41	50.3	5030	729	-	-	-	-
	A-2	1.102	0.44	31.2	3120	452	-	-	-	-
	A-3	1.156	0.47	24.4	2440	354	-	-	-	-
	A-4	1.325	0.62	14.1	1410	204	1.366	136.6	19.8	0.58
	A-5	1.337	0.65	10.8	1080	157	1.848	184.8	26.8	0.89
	A-6	1.580	0.84	10.0	1000	145	1.735	173.5	25.2	0.80
	A-7	1.590	0.91	7.26	726	105	2.310	231.0	33.5	1.31
	A-8	1.706	1.06	1.09/3.08	109/309	16/45	1.934	193.4	28.0	2.39

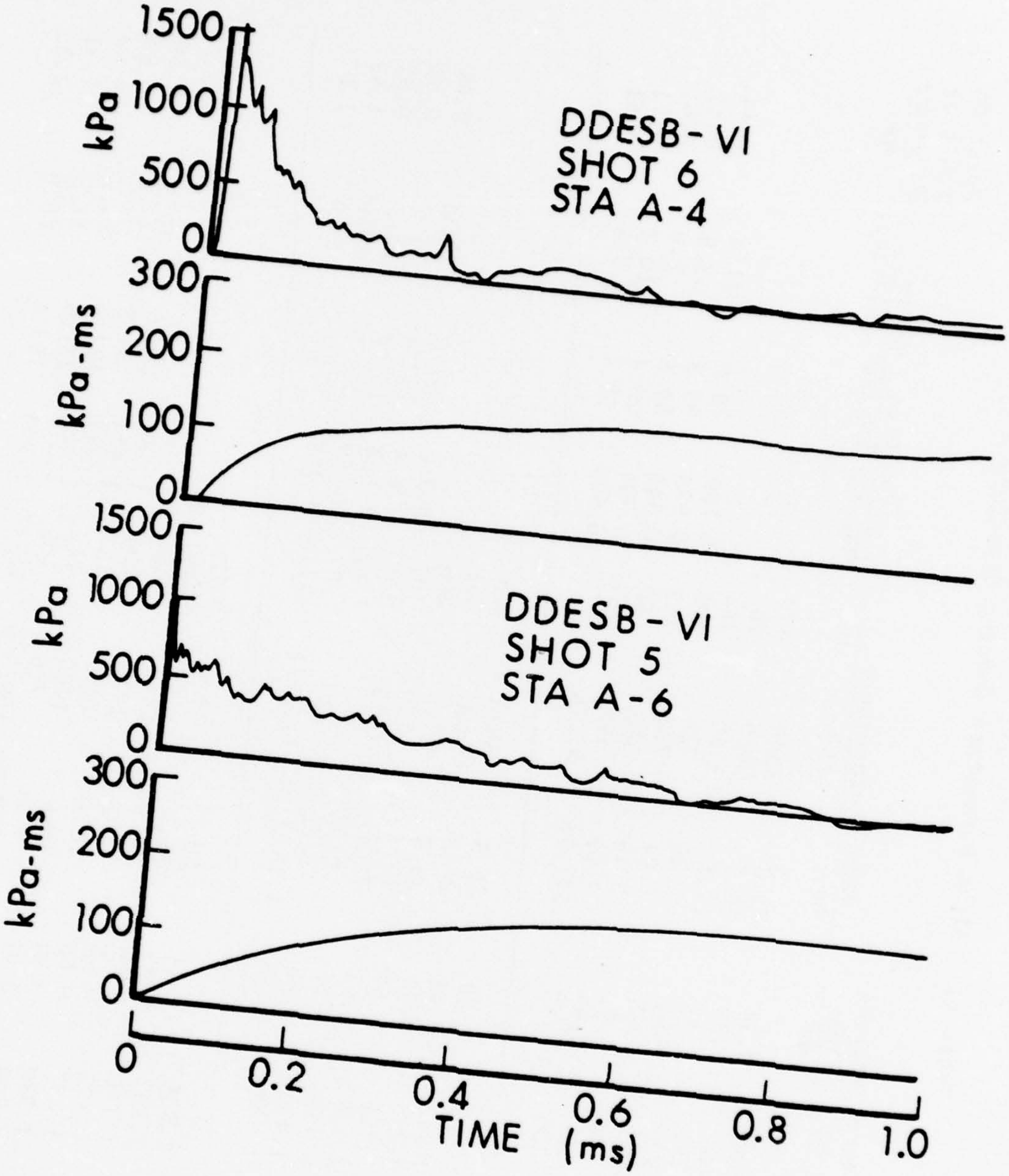

Figure 13. Overpressure and Impulse versus Time at Station A-4 and A-6, 1.792 kg Charge

This would be expected since Station A-6 is a greater distance from the explosive source. But the impulse recorded at Station A-6 is greater than recorded at Station A-4 (174 versus 137 kPa-ms). This is an important observation to be noted for structural designers when considering the blast load over the roof of the structure. Because of the expansion of the shockwave over the top, after moving up the slope, the decay of overpressure versus time is very fast at Station A-4 whereas at Station A-6, the peak overpressure is less, and the pressure decay is slower, and therefore, the overpressure impulse is greater.

The mean values of overpressures and impulses recorded on Structure B, located to the side of the donor, are listed in Table III. See Figure 11 for station locations.

The overpressures versus time recorded at Stations B-3, B-4, and B-5 are shown in Figure 14 for a 1.066 kg charge. This simulates a 133250 kg (294 000 lbs) of explosive in a full size storage magazine. Note that the peak overpressures are quite similar with a mean value of 460 kPa, but the pressure decay versus time varies slightly at the three stations. The overpressure impulses recorded at the three stations are 109, 113, and 107 kPa-ms giving a mean value of 110 kPa-ms. This value would represent 5500 kPa-ms for a full-size structure blast load or 798 psi-msec.

The blast parameters recorded on Structure C, facing the rear of the donor, as shown in Figure 11, are listed in Table IV. A discussion of shock interaction and the development of peak overpressures will be confined to the headwall only. The blast loading on the top of Structure C is much less than on Structures A or B and therefore would not influence the design. The loading on the headwall of Structure C consists of many complex reflection patterns and was documented with four gauge station locations as shown in Figure 15. Station C-4 was located at the approximate center of the magazine door. Results from the 1.066 kg charges were used for the following analysis. They simulate a full-size magazine containing 133 250 kg (294 000 lbs) of high explosive.

If we assume that when the blast wave propagates out of the rear of the donor magazines and travels down the rear slope, it tends to become perpendicular to the slope as shown in Figure 16. If upon reaching the ground surface the angle of incidence of the shock front is assumed to be 63.4 degrees then a Mach stem will form and the surface will be in the Mach reflection while above the triple point there will be an incident and reflected shock. Upon arrival at the structure, the headwall and door will be subjected to a very complex loading pattern including the reflection of the incident shock, reflected shock, and the Mach stem shock. The assumed profiles of the shocks striking the front of Structure C are shown in Figure 17.

If the angle of incidence is 63.4 degrees and the Mach pressure recorded at gauge F-1 is 333 kPa (48 psi), then the strength of the

Table III. Blast Parameters Loading Structure B

Charge Weight	Gauge Station	Distance from GZ	Arrival Time	Peak Overpressure			Positive Impulse			Duration Positive Pressure
kg		m	ms	bar	kPa	psi	bar-ms	kPa-ms	psi-msec	ms
0.357	B-1	0.334	0.42	7.57	757	110	1.405	140.5	20.4	0.85
	B-2	0.569	0.67	3.27	327	47	0.559	55.9	8.1	0.94
	B-3	0.525	0.69	2.66/3.40	266/340	39/49	0.702	70.2	10.2	0.73
	B-4	0.510	0.65	2.67/2.85	267/285	39/41	0.711	71.1	10.3	0.64
	B-5	0.525	0.68	3.06/4.02	306/402	44/58	0.754	75.4	10.9	0.65
	B-6	0.619	0.79	3.09	309	45	0.554	55.4	8.0	0.92
	B-7	0.687	1.02	1.03/1.65	103/165	15/24	0.486	48.6	7.0	1.09
1.066	B-1	0.496	0.57	9.44	944	137	1.941	194.1	28.1	0.83
	B-2	0.718	0.75	3.07/5.24	307/524	44/76	0.929	92.9	13.5	0.95
	B-3	0.684	0.76	4.96	496	72	1.086	108.6	15.8	0.90
	B-4	0.672	0.79	4.32	432	63	1.130	113.0	16.4	0.79
	B-5	0.684	0.78	4.53	453	66	1.070	107.0	15.5	0.83
	B-6	0.758	0.94	3.53	353	51	0.871	87.1	12.6	1.00
	B-7	0.849	1.03	2.41	241	35	0.837	83.7	12.1	1.21
1.792	B-1	0.592	0.55	14.2	1420	206	2.044	204.4	29.6	0.83
	B-2	0.809	0.77	4.28/5.00	428/500	62/72	1.264	126.4	18.3	0.98
	B-3	0.779	0.72	6.64	664	96	1.243	124.3	18.0	0.86
	B-4	0.768	0.71	5.52	552	80	1.289	128.9	18.7	0.94
	B-5	0.779	0.76	5.87	587	85	1.180	118.0	17.1	0.75
	B-6	0.845	0.87	4.69	469	68	1.021	102.1	14.8	1.00
	B-7	0.946	1.02	3.23	323	47	0.868	86.8	12.6	1.20

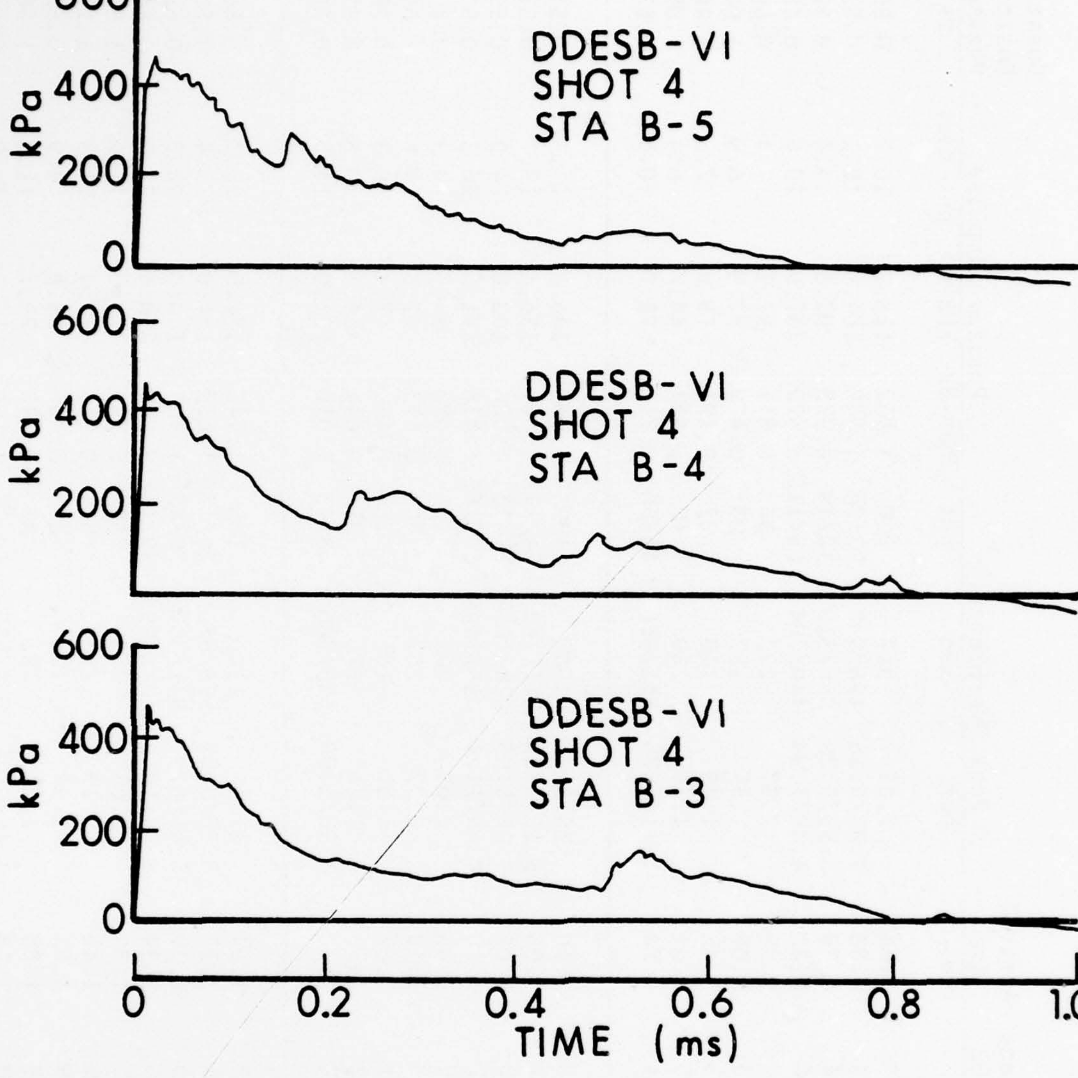

Figure 14. Overpressure versus Time, Station B-3, B-4, and B-5 for a 1.066 kg Charge

Table IV. Blast Parameters Loading Structure C

Charge Weight	Gauge Station	Distance from GZ	Arrival Time	Peak Overpressure			Positive Impulse			Duration Positive Pressure
kg		m	ms	bar	kPa	psi	bar-ms	kPa-ms	psi-msec	ms
0.357	C-1	0.814	0.86	9.67	967	140	1.152	115.2	16.7	0.50
	C-2	0.814	0.83	4.96/5.38	496/538	72/78	1.040	104.0	15.1	0.52
	C-3	0.814	0.79	5.50/3.39	550/339	80/49	0.923	92.3	13.4	0.59
	C-4	0.814	0.83	4.49/7.94	449/794	65/115	1.379	137.9	20.0	0.48
	C-5	0.942	0.98	2.37	237	34	0.511	51.1	7.4	0.89
	C-6	0.958	1.06	1.57	157	23	0.479	47.9	6.9	1.00
	C-7	1.193	1.43	1.49	149	22	0.194	19.4	2.8	0.46
	C-8	1.206	1.51	1.30	130	19	0.444	44.4	6.4	1.05
	F-1	0.754	0.74	3.11/3.88	311/388	45/56	0.750	75.0	10.9	0.57
1.066	C-1	1.082	1.10	10.8	1080	157	1.467	146.7	21.3	0.51
	C-2	1.082	1.08	5.11/7.82	511/782	74/113	1.361	136.1	19.7	0.51
	C-3	1.082	1.07	5.28/5.03	528/503	77/73	1.026	102.6	14.9	0.55
	C-4	1.082	1.10	4.15/11.4	415/1140	60/165	1.815	181.5	26.3	0.50
	C-5	1.210	1.25	2.63	263	38	0.683	68.3	9.9	0.87
	C-6	1.223	1.32	2.07	207	30	0.673	67.3	9.8	1.00
	C-7	1.461	1.67	1.81	181	26	0.434	43.4	6.3	0.79
	C-8	1.472	1.75	1.76	176	25	0.641	64.1	9.3	1.31
	F-1	1.022	1.02	3.33/5.06	333/506	48/73	1.010	101.0	14.6	0.64
1.792	C-1	1.220	1.24	11.4	1140	165	1.745	174.5	25.3	0.56
	C-2	1.220	1.22	5.23/8.53	523/853	76/124	1.610	161.0	23.4	0.53
	C-3	1.220	1.19	5.41/6.07	541/607	78/88	1.403	140.3	20.3	0.65
	C-4	1.220	1.24	4.04/10.9	404/1090	59/158	2.204	220.4	32.0	0.58
	C-5	1.348	1.39	2.68	268	39	0.790	79.0	11.5	1.01
	C-6	1.360	1.45	2.13	213	31	0.814	81.4	11.8	1.11
	C-7	1.599	1.81	1.98	198	29	0.336	33.6	4.9	0.52
	C-8	1.609	1.88	1.81	181	26	0.782	78.2	11.3	1.38
	F-1	1.160	1.16	3.45/5.35	345/535	50/78	1.160	116.0	16.8	0.66

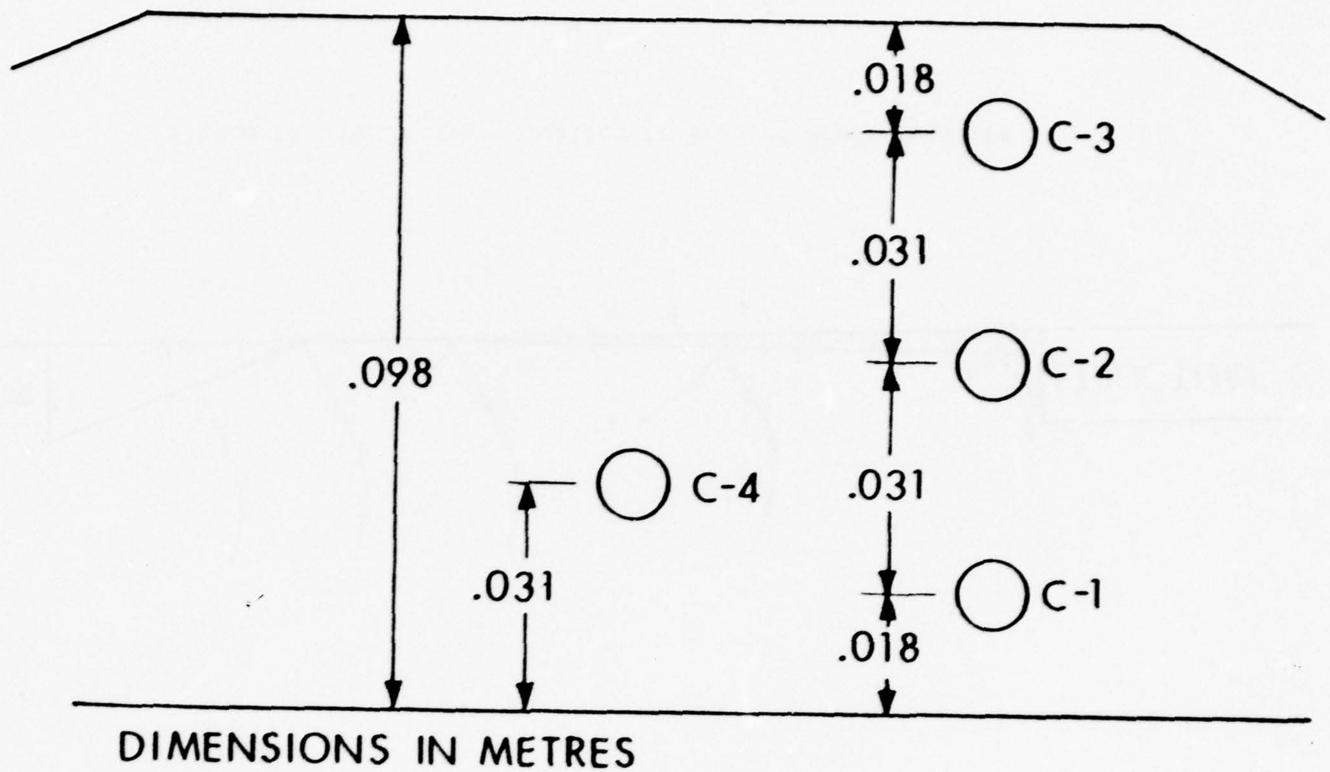

Figure 15. Station Locations on Headwall of Structure C

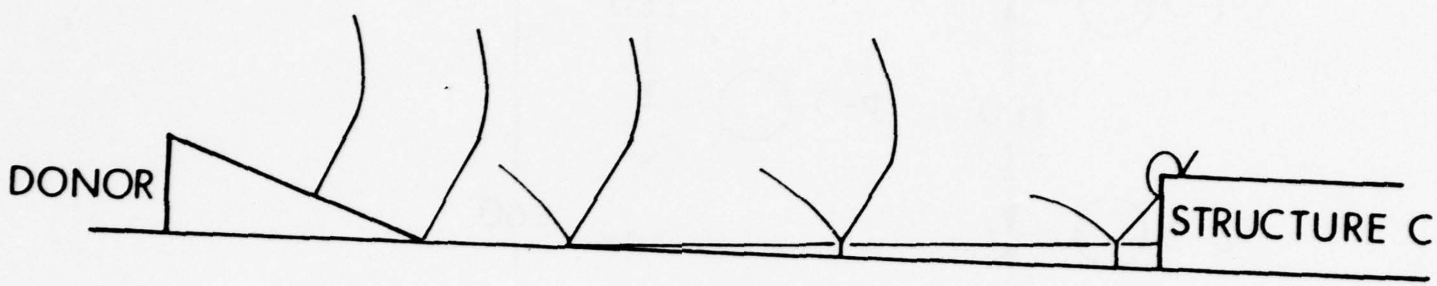

Figure 16. Mach Stem Formation to Rear of Donor Magazine

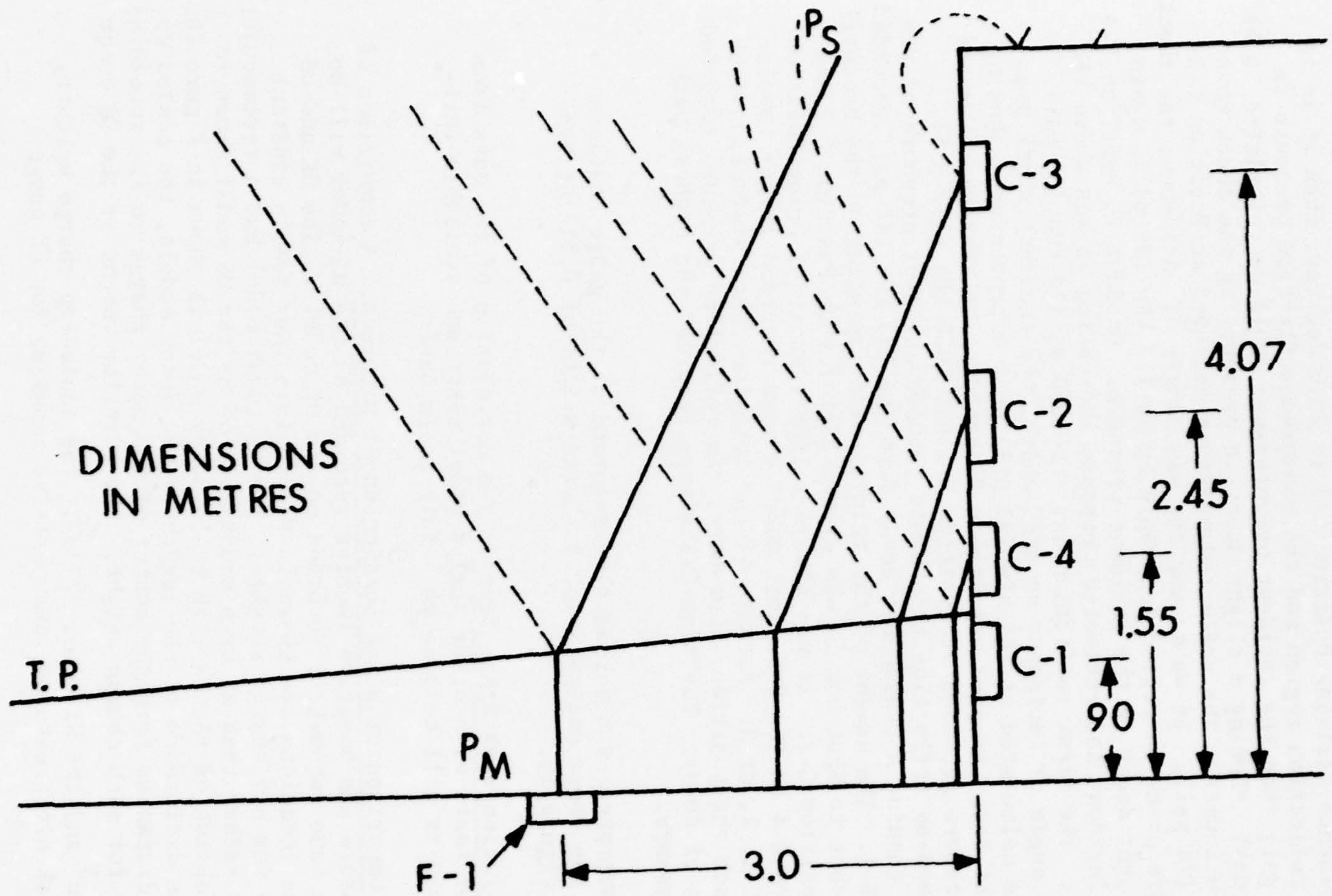

Figure 17. Shock Interaction on Headwall of a Full-Scale Structure C

incident shock wave is calculated as 193 kPa (28 psi). If we assume the angle of incidence striking Position C-3 is 26.6 degrees, then it is in the regular reflection region and the measured reflection pressure is 528 kPa (77 psi) then the incident overpressure would be calculated to be 179 kPa (26 psi), showing a slight decay in pressure as the shock moves away from the source. The reflected pressure measured at Position C-2 was 511 kPa (74 psi). If we assume the same angle of incidence, the shock front pressure prior to reflection would be as 172 kPa (25 psi), again showing a slight decay in the incident pressure. On Shot 2, Position C-4 recorded an incident and reflected pressure indicating it was above the triple point. The first reflection was recorded as 414 kPa (60 psi). For the same angle of incidence as used above, the incident shock pressure would be calculated at 145 kPa (21 psi) peak overpressure, showing again a slight decay in pressure versus distance. The average reflected Mach stem pressure recorded at Position C-1 was 1080 kPa (157 psi). Assuming a head-on reflection this would require an input pressure of 289 kPa (42 psi) showing a reasonable decay from the 333 kPa (48 psi) recorded at Position F-1. The height of the triple point impinging on the headwall varied from shot to shot but it was always higher than Position C-1 and lower than Position C-2. It was always slightly above or below Position C-4. Position C-4 on the U.S. test model always recorded larger impulse values than C-1, 2, or 3. Because of the location, the rarefaction took longer to reach the position, therefore, the reflection pressure recorded a slower rate of decay. Position C-1 always recorded the highest peak reflected pressure.

The overpressures versus time recorded at the gauge stations mentioned in the above analysis for a charge weight of 0.357 kg are presented in Figure 18.

4. Correlation with Other Tests. The correlation of the data from this series of tests with other scaled model tests and available full-scale test results will be done on a full-scale basis.

a. Comparison of Blast Loading on Structure A. A comparison of peak overpressure and positive impulse recorded on the US model will be made with the same parameters recorded on the UK model[5]. The UK and US relative gauge locations are shown in Figure 19. They remain constant on the models for all charge weights. The UK donor model had a rectangular cross-section rather than an arch cross-section as the US model shown in Figure 1. A sketch of the UK 1/10 scale donor model is shown in Figure 20. Because of the difference in the length of the donor models, the scaled-up or full size distances from the center of the donor charge to the recording stations vary for each charge weight. The interior volume of the US donor would be 600 m^3 and the UK donor 729 m^3. The scaled-up charge weights, distances, peak overpressures, and positive impulses for UK gauge

[5] *UK Report, "Blast and Projections from Model Igloos," Report No. ENT 124-76, Proof and Experimental Establishment, Shoeburyness.*

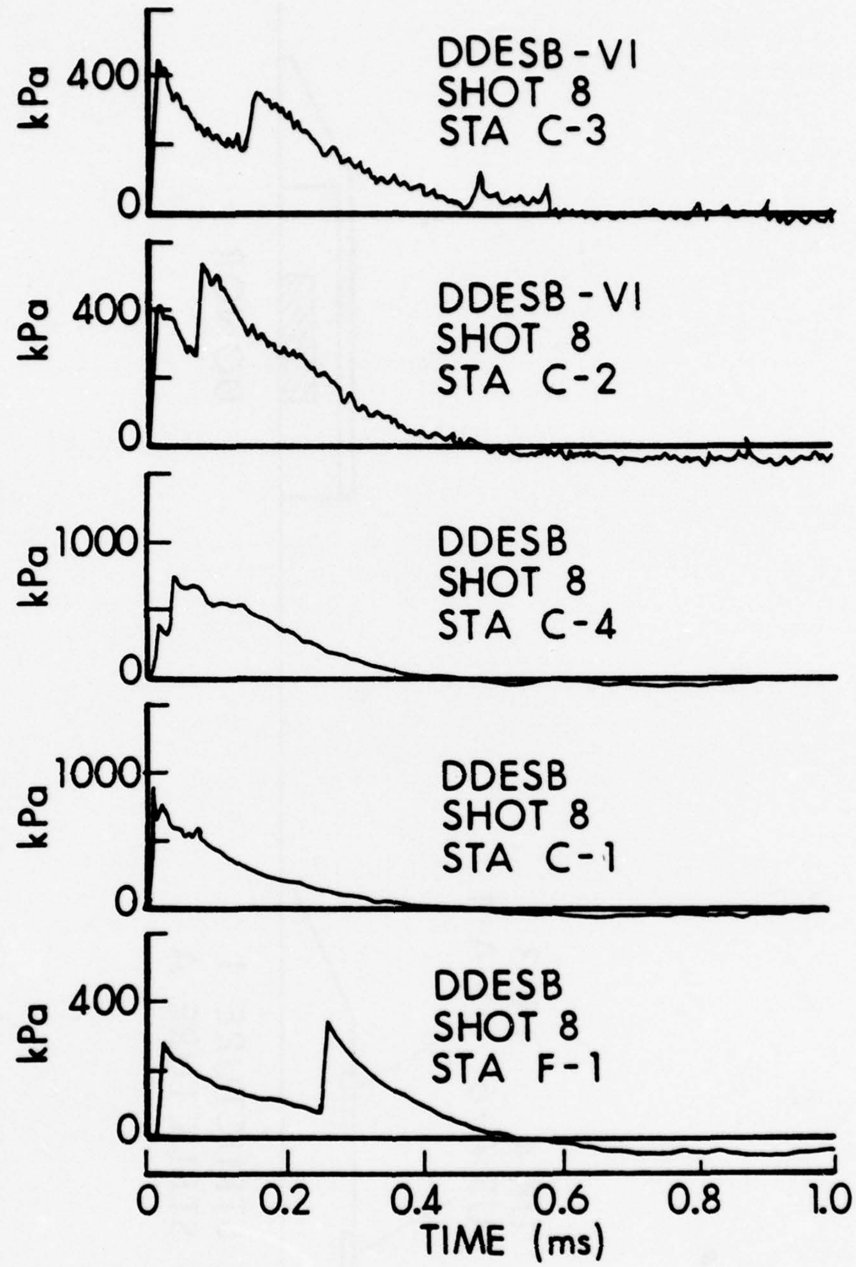

Figure 18. Shock Wave Profiles Recorded on Front of Structure C

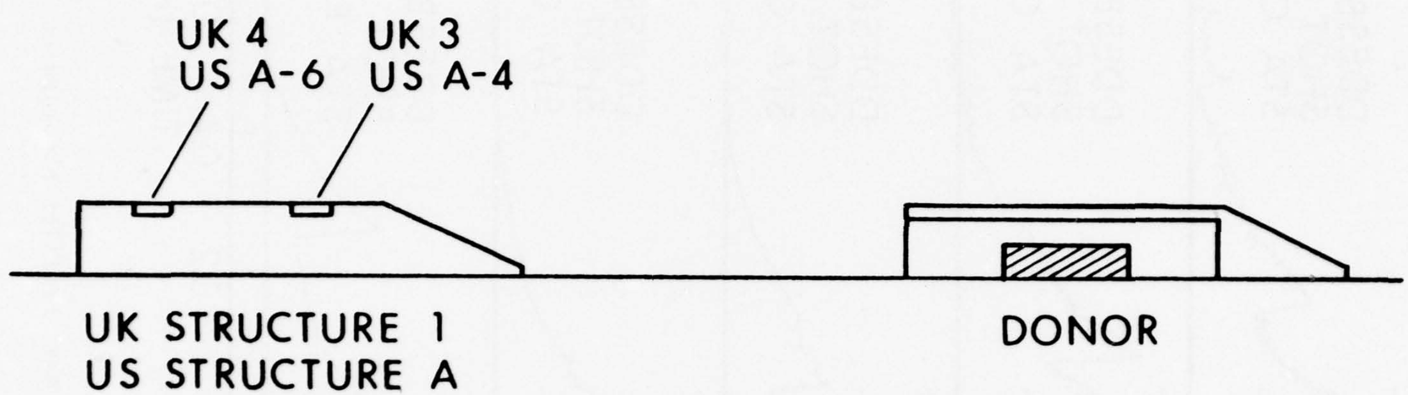

Figure 19. US and UK Gauge Locations on Structure A

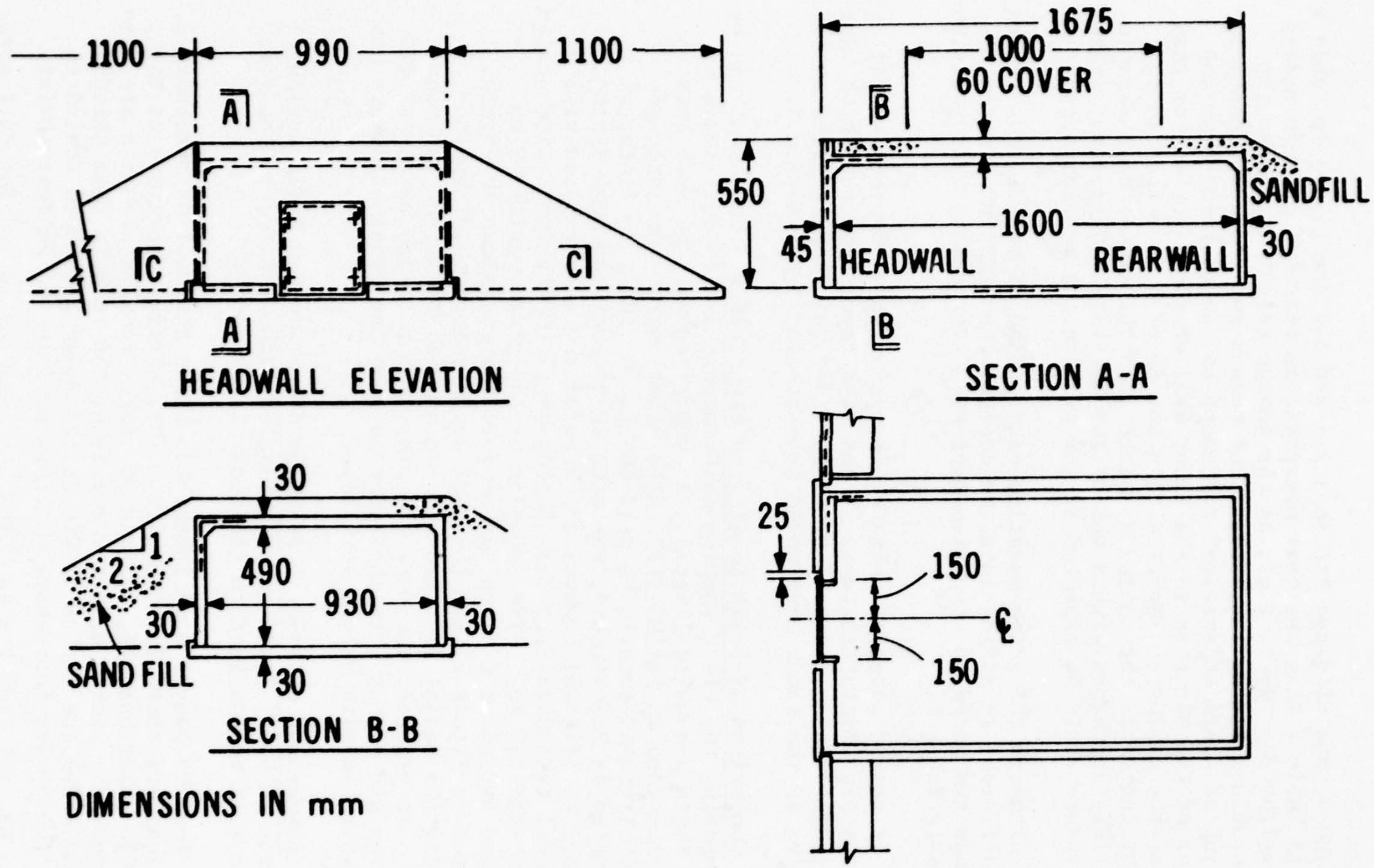

Figure 20. UK 1/10th Scale Donor Magazine

Stations 3 and 4, and US gauge Stations A-4 and A-6 are listed in Table V. It appears in Table V that the peak overpressure recorded on both models are charge weight dependent; i.e., as the charge weight increases the overpressure values listed increases. One reason for this dependency is the definition of "safe separation" distances as the distance from the rear interior of the acceptor to the front wall of the donor rather than the center of the explosive source within the donor. Note that as the charge weight increases the scaled distance from the center of the explosive source (GZ) decreases within the UK and US tests. Therefore, higher peak overpressure would be expected at the smaller scaled distances.

Although the donor magazine used in the UK and US test series were quite different in scale, interior design, and structural materials; similar trends are noted in comparisons of peak overpressure and positive impulse made in Table V.

It should be noted that for charge weights greater than 44 625 kg, there is a significant increase in positive impulse as the shock wave moves from gauge Station A-4 to A-6. This trend was also recorded on the UK test series as the shock wave moved from Station 3 to Station 4.

b. Comparison of Blast Loading on Structure B. Data that can be used for comparing the blast loading on Structure B with full-scale or other model tests are quite limited. A comparison will be made between the results recorded on ESKIMO III[4]. The donor charge consisted of 158 900 kg of Tritonal encased in M117 bombs. A reduction factor of 0.753, presented in Reference 4, was used to account for bomb casing, giving 119 652 kg Tritonal equivalent. Therefore, a comparison will be made with model test data from Test Series II (1.066 kg) pentolite scaled to full size (133 250 kg). The location of the gauge positions on ESKIMO III and Structure C along the center line are shown in Figure 21. Also presented in Figure 21 are the peak overpressures and impulses measured along the radial from ground zero on ESKIMO III and the model Structure B. In general, the peak overpressures recorded on the ESKIMO III structures are higher than those recorded on the model structure but the overpressure impulse values were lower.

c. Comparison of Blast Loading on Structure C. A discussion of the comparison of blast loads on a storage magazine located to the rear of the donor will be confined to the headwall and door.

Four US gauges were installed on the headwall of Structure C. These locations are shown in Figure 22. The relative locations of the three UK gauge positions, 18, 19, and 20, taken from Reference 5 are also shown in Figure 22. For a direct comparison, the results from the US 1/50th scaled model and the UK 1/10th scaled model have been scaled to full size. There were four charge weights used in the UK test series. They were 8, 64, 125, and 216 kg. The scale factor is 10^3 for full size. Results of the peak overpressure on the front headwall and door of a full size structure are presented in Table VI. The positive impulses on the same full size structure are presented in Table VII.

Table V. Comparison of Blast Loading on Acceptor Structure in Front of Donor

Reference	Charge Weight	Distance from GZ		Peak Overpressure		Overpressure Impulse		Scaled Distance		Scaled Impulse	
		UK-3 US-A4	UK-4 US-A6	UK-3 US-A4	UK-4 US-A6	UK-3 US-A4	UK-4 US-A6	UK-3 US-A4	UK-4 US-A6	UK-3 US-A4	UK-4 US-A6
	kg	m	m	kPa	kPa	kPa-ms	kPa-ms	$m/kg^{1/3}$	$m/kg^{1/3}$	$kPa\text{-}ms/kg^{1/3}$	$kPa\text{-}ms/kg^{1/3}$
UK	8000	27	42	303	76	-	1380	1.35	2.10	-	69
US	44625	46	59	726	346	3950	2730	1.30	1.66	111	77
UK	64000	43	58	855	503	4000	6960	1.08	1.45	100	174
UK	125000	51	66	1117	621	4830	5390	1.02	1.32	97	108
US	133250	58	71	1150	662	6550	7770	1.14	1.39	128	152
UK	216000	59	74	910	1331	7520	7580	0.98	1.23	125	126
US	224000	66	79	1410	1000	6830	8670	1.09	1.30	112	143

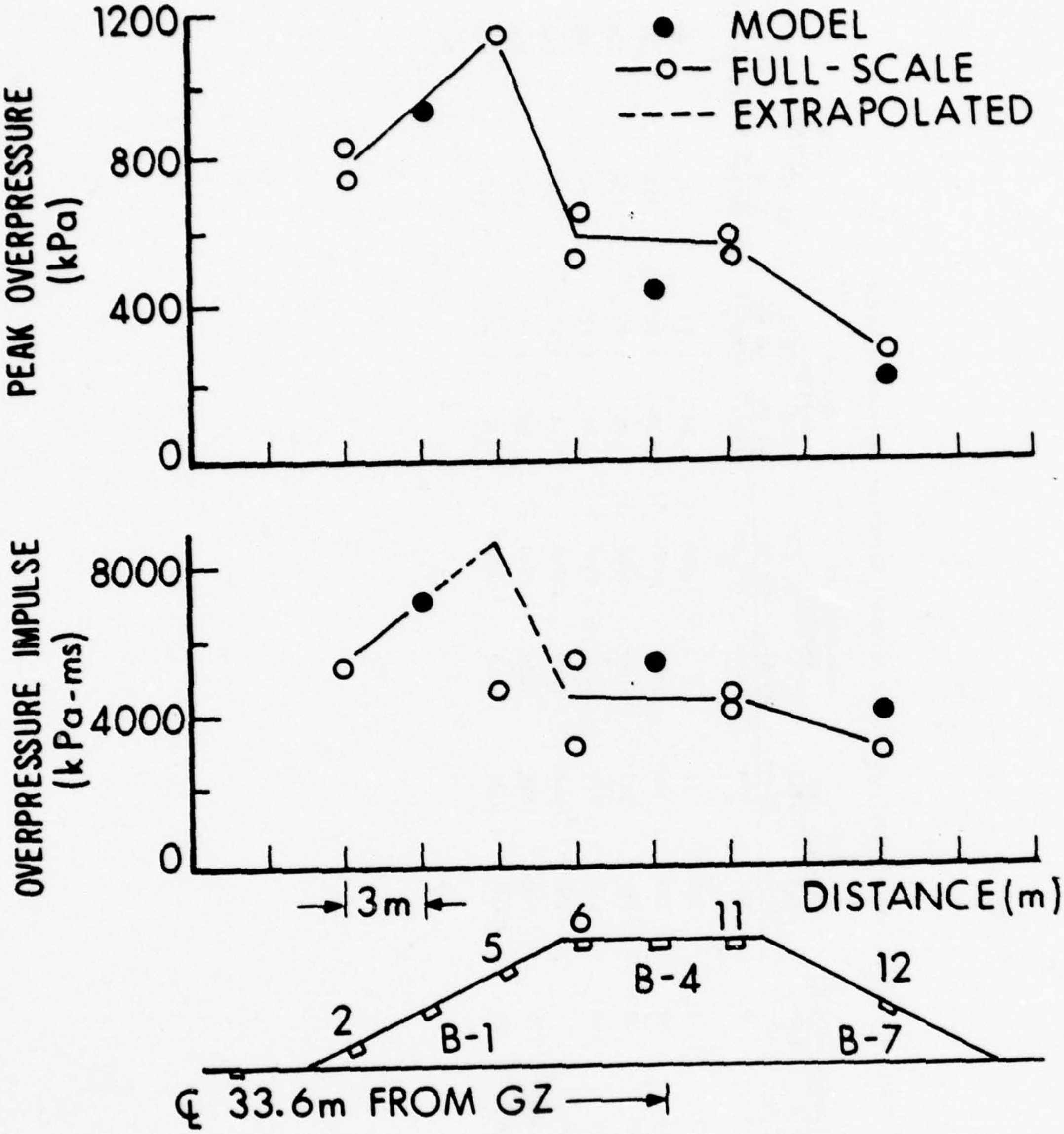

Figure 21. Comparison of Peak Overpressure and Impulses on Model and Full-Scale Structure B

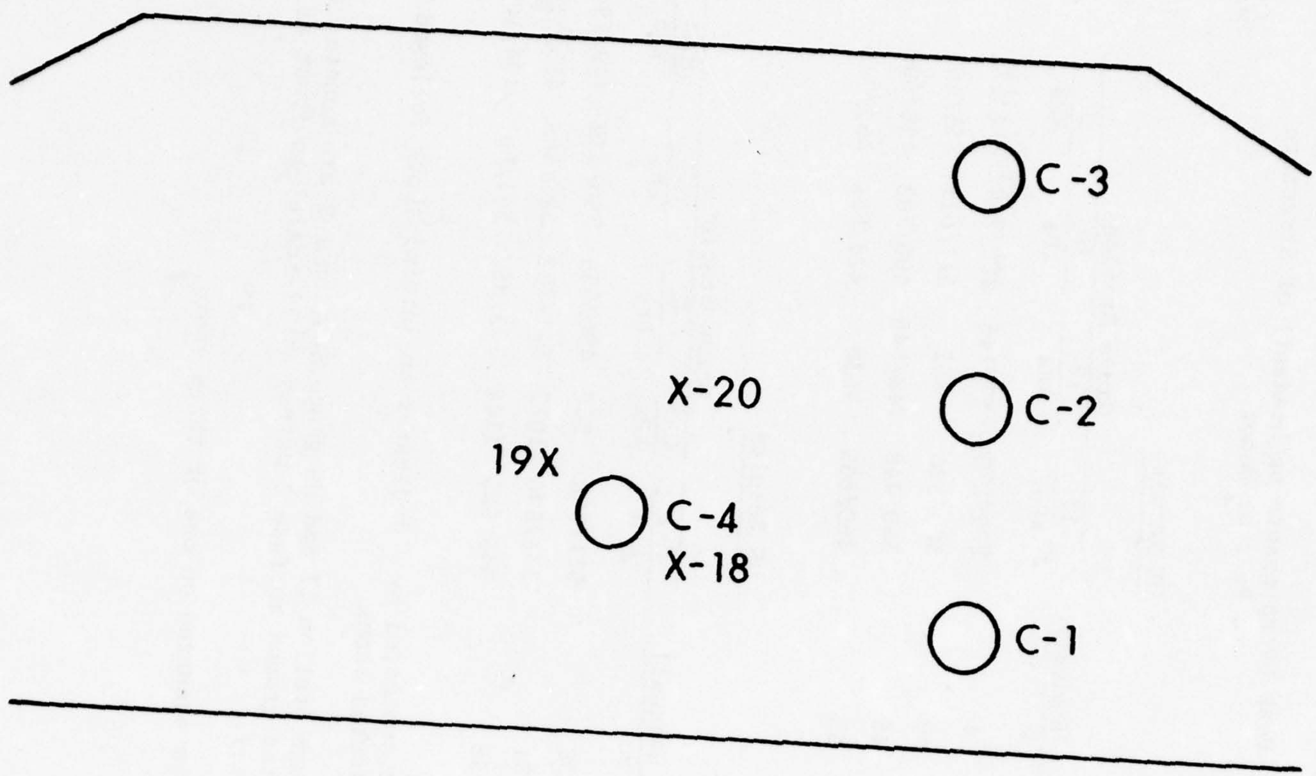

Figure 22. Gauge Locations on US Model Structure C and UK Model Structure 3

Table VI. Peak Overpressure on Headwall of Structure to Rear of Donor

UK Results

Charge Weight kg	GZ to Headwall m	Gauge Stations 17 kPa	18 kPa	19 kPa	20 kPa
8000	24	225/170	97/145	200/248	214/172
64000	40	300/326	862	317/621	331/493
125000	45	350/448	448/848	400/793	428/690
216000	53	360/665	1630	421/834	462/745

US Results

Charge Weight kg	GZ to Headwall m	Gauge Stations F-1 kPa	C-1 kPa	C-2 kPa	C-3 kPa	C-4 kPa
44625	38	311/388	967	496/538	550/339	449/794
133250	51	333/506	1075	511/782	528/503	415/1140*
224000	58	345/525	1144	523/853	541/607	404/1092*

NOTE: 1. Values separated by / indicates an initial shock followed by a reflected shock.

2. UK gauge Station 17 and US gauge Station F-1 are mounted flush with the ground surface 3 metres (full-scale) in front of the headwall.

*Two shocks occurred on one of three shots.

Table VII. Positive Impulse on Headwall of Structure to Rear of Donor

UK Results

Charge Weight	GZ to Headwall	Gauge Stations			
		17	18	19	20
kg	m	kPa-ms	kPa-ms	kPa-ms	kPa-ms
8000	24	2010	1850	2270	2190
64000	40	3780	5770	5120	5030
125000	45	5720	8370	7810	7830
216000	53	6880	10780	9640	9430

US Results

Charge Weight	GZ to Headwall	Gauge Stations				
		F-1	C-1	C-2	C-3	C-4
kg	m	kPa-ms	kPa-ms	kPa-ms	kPa-ms	kPa-ms
44625	38	3750	5760	5200	4610	6900
133250	51	5050	7340	7280	5130	9080
224000	58	5800	8720	8050	7010	11020

See Note 2 of Table VI.

Because of the sensitivity of the peak values of the reflected shocks to arrival times and the height of the Mach stem, the comparison of overpressure impulse loading on the headwall and door is much better than the peak overpressure values. The UK gauge stations are rather closely grouped and there is only a small spread in the three impulse values recorded on each shot. The US gauge stations are widely spaced and since the impulse is a function of gauge location it can be seen that Station C-4 always recorded the largest overpressure impulse values and Station C-3, because it was closest to the source of a rarefaction wave, always recorded the smallest positive impulse for specific yields.

D. Blast Loading on Off-Line Acceptor Magazines

The blast loading on structures to the front and rear of a donor magazine is quite severe at the present safe-separation distances. The DDESB is in a constant search for cost effective means of reducing blast loading on munition magazines and therefore requested the BRL to study the effects of off-line placement of magazines.

1. Objective. The objective of this series of tests was to determine the reduction, if any, of blast loading on acceptor magazines to the front and rear of a donor when placed off-line; i.e., not directly in-line.

2. Test Procedure. The dimensions of the 1/50 scale donor and acceptor models are shown in Figure 1 and Table I. The instrumentation system is the same as shown in Figure 4. Only two charge weights were used. They were 1.066 and 1.792 kg of Pentolite in a hemicylindrical configuration. The test layout and gauge positions are shown in Figure 23. The test was designed so that direct comparisons of blast parameters could be made between Acceptor A and C of the previous series and Acceptor D, E, and G of this series. A photograph of the donor and acceptor models in test positions are shown in Figure 24.

3. Results. The results presented in this paper will be limited to a comparison of the blast loading on the top of Structures A, D, and E, and the headwall loading on Structures C and G.

The peak overpressure and impulse recorded on the two structures to the front of the donor are presented in Table VIII. It should be noted from the test layouts that the distance from the center of the explosive source is greater to the off-line gauge stations than the in-line stations. As might be expected, the peak overpressures recorded at the off-line stations are lower than those recorded at the in-line stations with one exception, Station A-6 (1.066 kg) recorded a lower mean value of peak overpressure than the corresponding location off-line station. The impulse values as noted earlier on the in-line tests increase from gauge Station A-4 to Station A-6 although the distance from the center of the explosive is increased. This same trend was also recorded for the off-line tests. The phenomenon that was not expected was that the impulse recorded at the corresponding gauge stations are

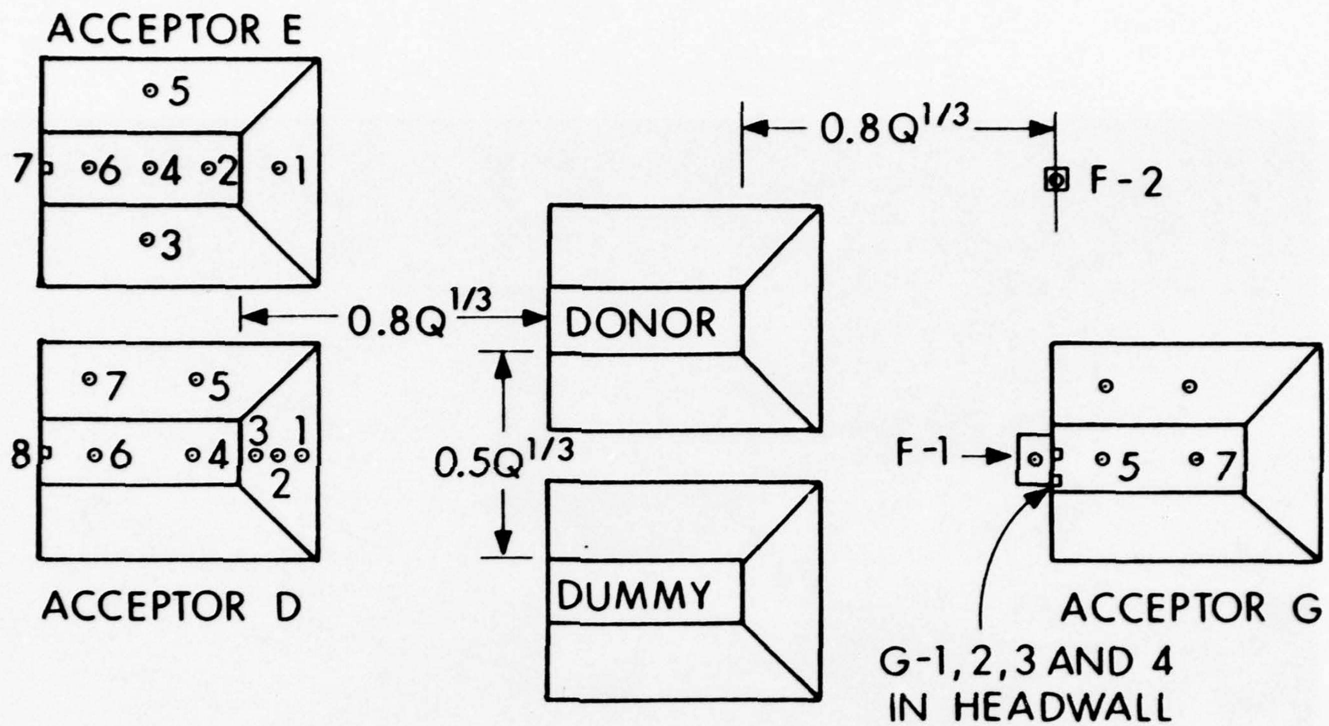

Figure 23. Test Layout for Off-Line Configuration

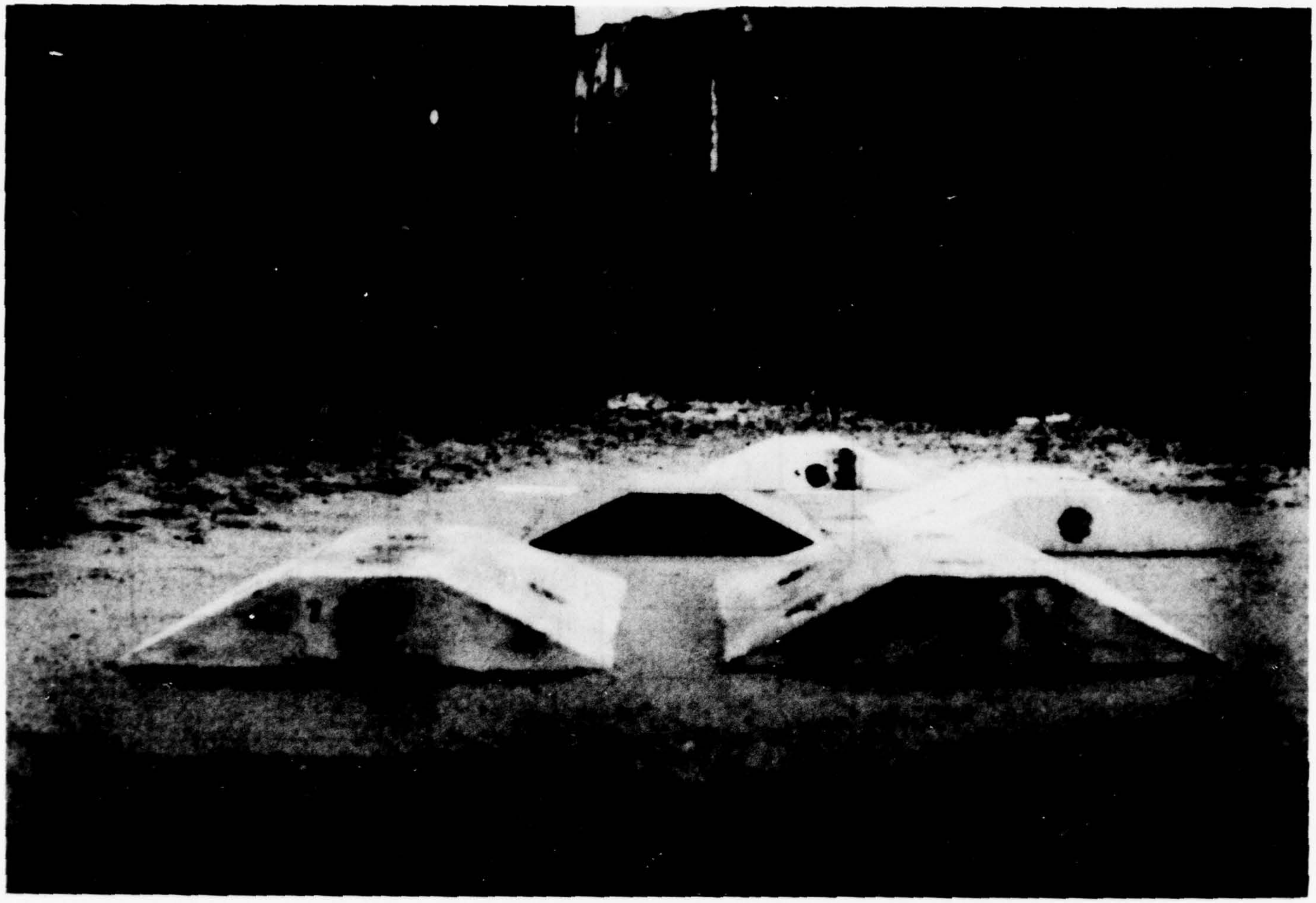

Figure 24. Photograph of Donor and Acceptor in Off-Line Positions

Table VIII. Results from In-Line and Off-Line Tests for Structures in Front of Donor

Charge Weight	Overpressure Position		Impulse Position		Overpressure Position		Impulse Position	
kg	A-4 kPa	D-4 kPa	A-4 kPa-ms	D-4 kPa-ms	A-6 kPa	D-6 kPa	A-6 kPa-ms	D-6 kPa-ms
1.066	1150	812	131	166	662	689	155	171
1.792	1410	949	137	177	1000	726	174	240
	A-4 kPa	E-2 kPa	A-4 kPa-ms	E-2 kPa-ms	A-6 kPa	E-6 kPa	A-6 kPa-ms	E-6 kPa-ms
1.066	1150	913	131	165	662	722	155	227
1.792	1410	1038	137	199	1000	678	174	244

much greater when the structures are in the off-line configuration. This may nullify any gain in the lowering of the peak overpressure. At Station E-6 a value of 244 kPa-ms was recorded. This would scale up to 12 200 kPa-ms (1769 psi-msec) on a full size magazine from a donor loaded with 224 000 kg (493 500 lbs) TNT. The in-line load under the same conditions would be 8700 kPa-ms (1261 psi-msec).

A plot of the overpressure and impulse versus time recorded at Stations A-4 and D-4 are presented in Figure 25. Here it can be seen that at Station A-4 the peak overpressure is higher but the positive impulse is lower than D-4. In Figure 26, a similar presentation is made for records from Stations A-6 and D-6. Here again Station A-6 records a higher peak overpressure but lower positive impulse than Station D-6. Note that the impulse recorded at Stations A-6 and D-6 are much higher than that recorded at Stations A-4 and D-4.

The results of the blast loading on the headwall and door of Structure C (in-line) and Structure G (off-line) are presented in Table IX. The conclusions to be reached from the data presented in Table IX are that the Structure G headwall is a greater distance from the center of the explosive source and therefore the reflected overpressures are lower at the four headwall stations on Structure G than Structure C. It is of interest to note that the overpressure impulse is almost identical at Stations 1, 2, and 3 on both structures while the impulse recorded at Station C-4 is approximately 27 percent greater for both charge weights than that recorded at Station G-4. All values in Table IX are mean values based on three shots under similar conditions.

4. Summary. Based on the results obtained from the in-line and off-line configurations it is apparent that the peak overpressures loading the top of structures to the front of a donor can be reduced by placing the acceptor structures off-line to the donor. However, there is a significant increase in the overpressure impulse for the off-line structures to the front of the donor which would probably nullify the reduction in peak overpressure.

There is a significant reduction of peak overpressure on the headwall of the structure to the rear of the donor when placed in the off-line position. The overpressure impulse is approximately the same over most of the headwall but with approximately a 22 percent reduction in overpressure impulse on the magazine door, Station G-4, when in the off-line configuration.

E. Blast Loading on Front to Side Configuration

Following the tests with acceptor structures placed in the off-line configuration the BRL was requested to document the blast loading on structures placed to the side of a donor with the headwall facing the donor.

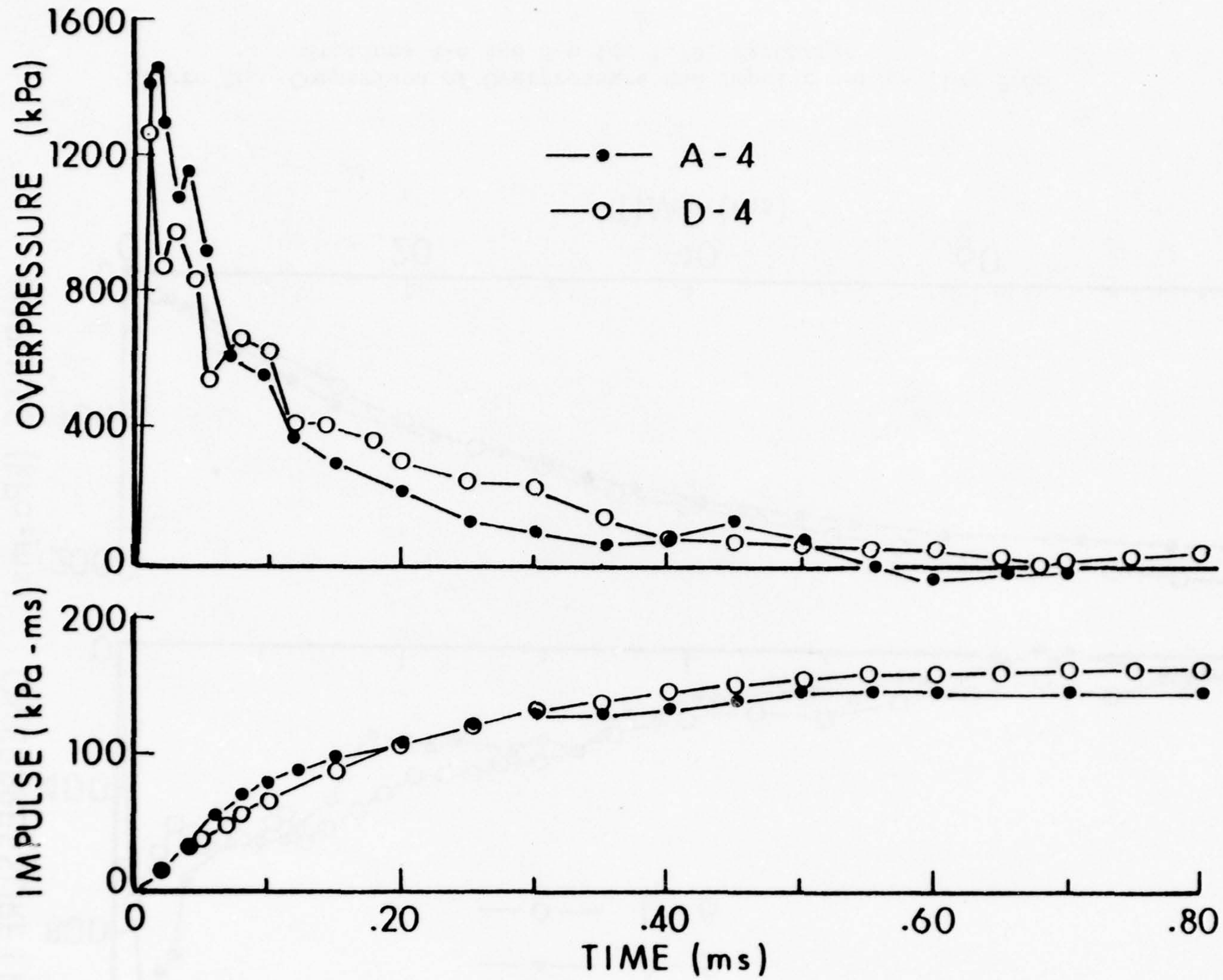

Figure 25. Comparison of Overpressure and Impulse versus Time from Stations A-4 and D-4 for 1.792 kg Charge

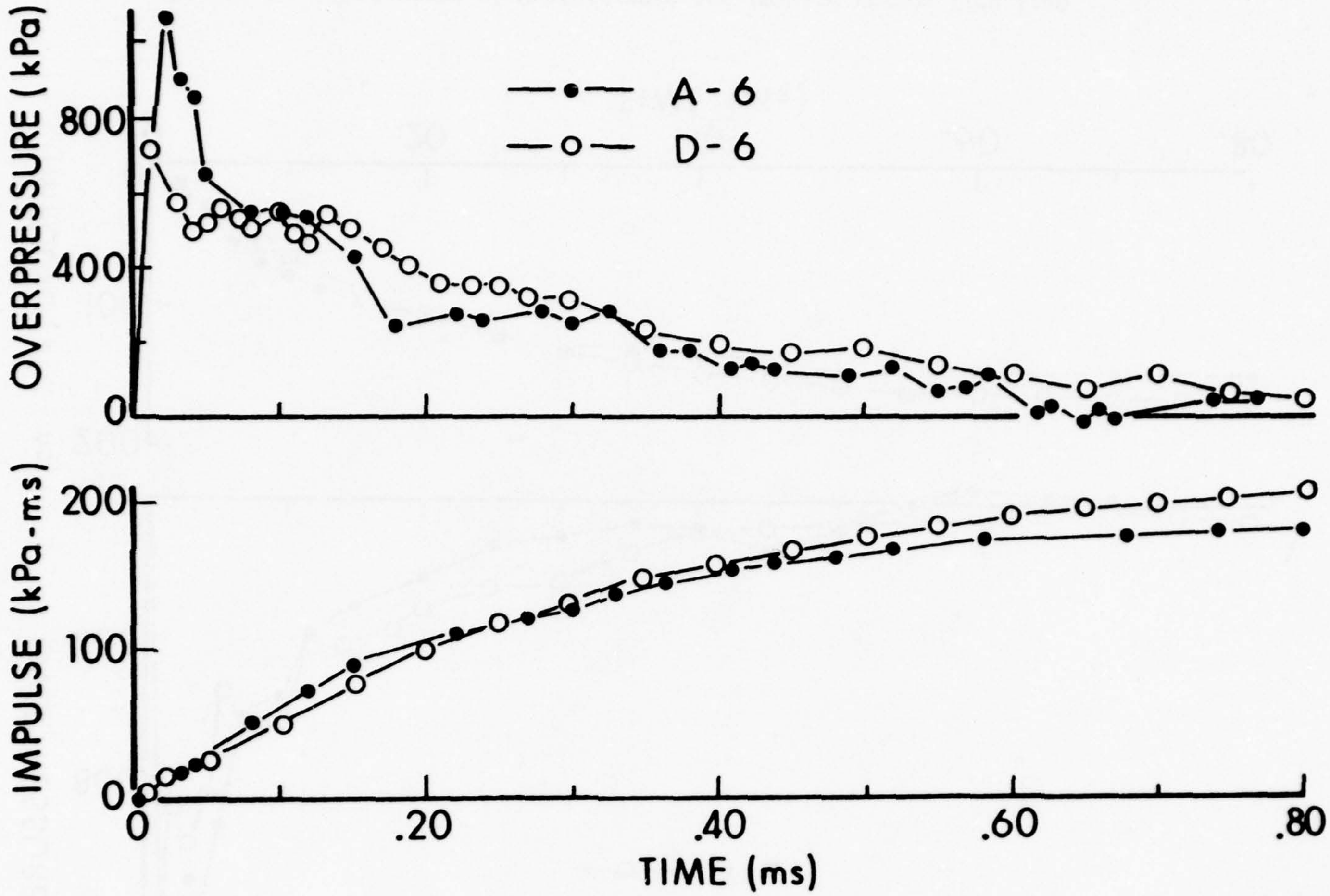

Figure 26. Comparison of Overpressure and Impulse versus Time from Stations A-6 and D-6 for 1.792 kg Charge

Table IX. Results from In-Line and Off-Line Tests for Structure to the Rear of Donor

Charge Weight	Structure	Peak Overpressure, kPa Position				Impulse, kPa-ms Position			
		1	2	3	4	1	2	3	4
1.066	C	1080	511/782	528/503	415/1140	147	136	103	182
1.066	G	823	368/611	382/467	334/740	148	131	114	145
1.792	C	1140	523/853	541/607	404/1090	174	161	140	220
1.792	G	858	412/689	455/495	390/863	174	160	137	171

1. Objective. The objective of this series of tests was to determine the blast loading on a structure placed to the side of a donor at the safe separation distance of $1.1Q^{1/3}$ ($2.75\ W^{1/3}$).

2. Test Procedure. The donor and acceptor models were 1/50th scale. The dimensions are given in Figure 1 and Table I. The instrumentation system is shown in Figure 4. There was only one charge weight fired in this series of tests. The mean value of the weights used was 1.076 kg which would represent 134 500 kg of explosive in a full size donor magazine. The test layout is shown in Figure 27. The gauge station locations on the front headwall are the same as shown in Figure 15. The gauge designations are Station H-1, H-2, H-3, and H-4.

3. Results. The blast parameters recorded at Stations H-1 through H-8 are listed in Table X. Also listed in Table X are the values recorded at Station F-1 located 0.06m in front of Structure H. The front of the structure appeared to be loaded with a vertical shock wave in that the arrival time at Stations H-1, H-2, and H-3 are the same. It appears that the loading on the structure is being influenced by the strong shock propagating out of the front of the donor structure in that the arrival time is shorter at Station H-4 than H-1, H-2, and H-3. Also the shock front reaches Station H-6 prior to H-5 and H-8 prior to H-7. The reflected pressure on the headwall is in the same range as recorded on Structure C for the same donor charge weight. See Table IV for the 1.066 kg charge weight. The peak overpressure recorded at Station C-1 is 1080 kPa while Station H-1 recorded 914 kPa.

4. Summary. The major difference is the overpressure impulse which is much higher on the headwall of Structure H than Structure C. Impulse recorded at Station C-1 was 147 kPa-ms while Station H-1 recorded 243 kPa-ms. This would be an impulse load of 1065 psi-msec versus 1762 psi-msec on a full size magazine from a donor loaded with 133 250 kg (293 600 lbs) of explosive. It should also be noted that the peak overpressure loading on the top of the Structures C and H are within ±5 percent of each other but the impulse at Station C-5 is 68 kPa-ms versus 109 kPa-ms at Station H-5. Station C-7 recorded an impulse of 43 kPa-ms while Station H-7 recorded 96 kPa-ms. These impulses recorded on the top of Structure H are much less than recorded on Structure A and therefore would not be used for the design criteria.

F. Model Studies for ESKIMO VI

This program will, in part, provide technical data in support of ESKIMO VI, a large-scale test of earth covered magazines planned for calendar year 1979.

1. Objective. The primary objective of these model tests is to evaluate the blast loadings on large, flat-roofed earth-covered magazines to the front, to the side, and to the rear of one such magazine as donor. The purpose of this type of experiment is to determine the actual loadings

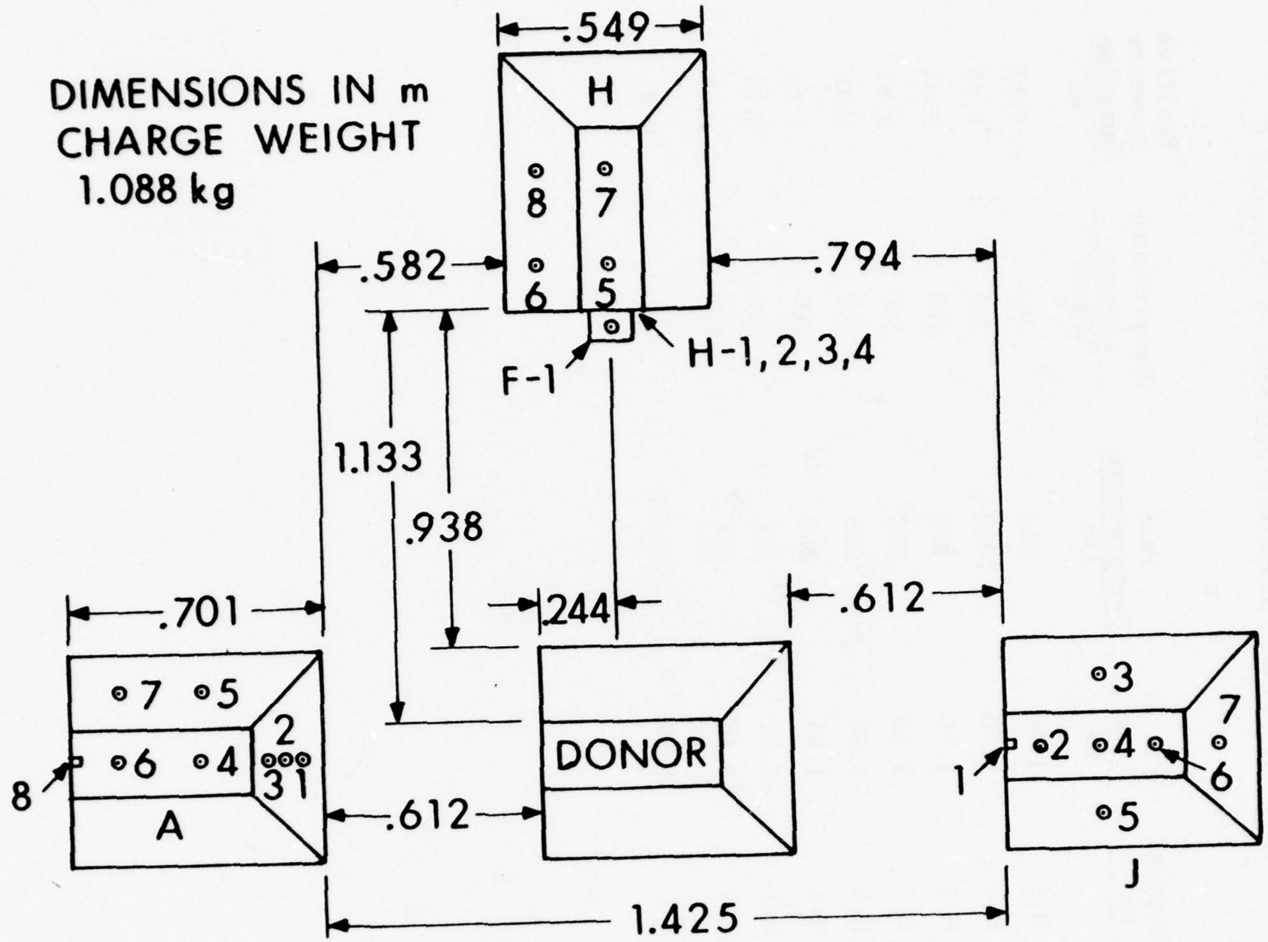

Figure 27. Test Layout for Front-to-Side Configuration

Table X. Blast Parameters Recorded on Structure H

Station No.	Arrival Time ms	Peak Overpressure kPa	Overpressure Impulse kPa-ms	Positive Pressure Duration ms
H-1	1.70	914	243	0.81
H-2	1.70	1010	235	0.88
H-3	1.70	972	208	0.94
H-4	1.68	952	246	0.83
H-5	1.88	276	109	1.48
H-6	1.84	260	119	1.65
H-7	2.32	171	96	1.79
H-8	2.30	225	108	1.45
F-1	1.59	280/671	186	0.91

to be expected on the roofs and front walls of large box-type magazines that are planned for exposure on ESKIMO VI.

2. Test Procedure. A 1/50th scaled model of the Smokeless Powder and Projectile Magazine, Type II-B will be used for the model tests. A non-responding model of cast concrete, with shock mounted gauges, will be used for the acceptor models as shown in Figure 28. The donor model will be constructed of masonite and plywood interior with a special modeling sand for the earth cover. A sketch of the donor model is shown in Figure 29. The instrumentation system will be the same as shown in Figure 4. The planned test site is shown in Figure 30. The safe separation distances are based on 158 865 kg (350 000 lbs) of explosive which scales by 50^3 down to 1.27 kg (2.8 lbs). The explosive source will consist of three pentolite charges placed to form an H. The detonation will start at the center of the cross bar. This charge configuration was used in the UK experiments reported in Reference 5.

3. Results. The results obtained from this planned test series will be used to guide the design of the full-size ESKIMO VI field experiment.

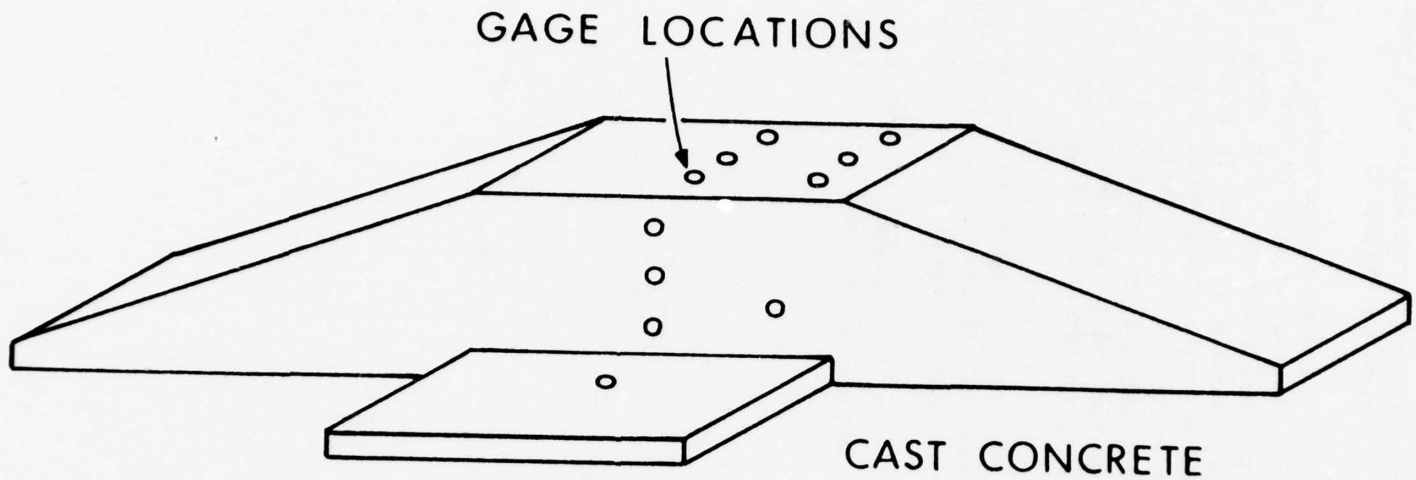

Figure 28. 1/50 Scale ESKIMO VI Acceptor Model

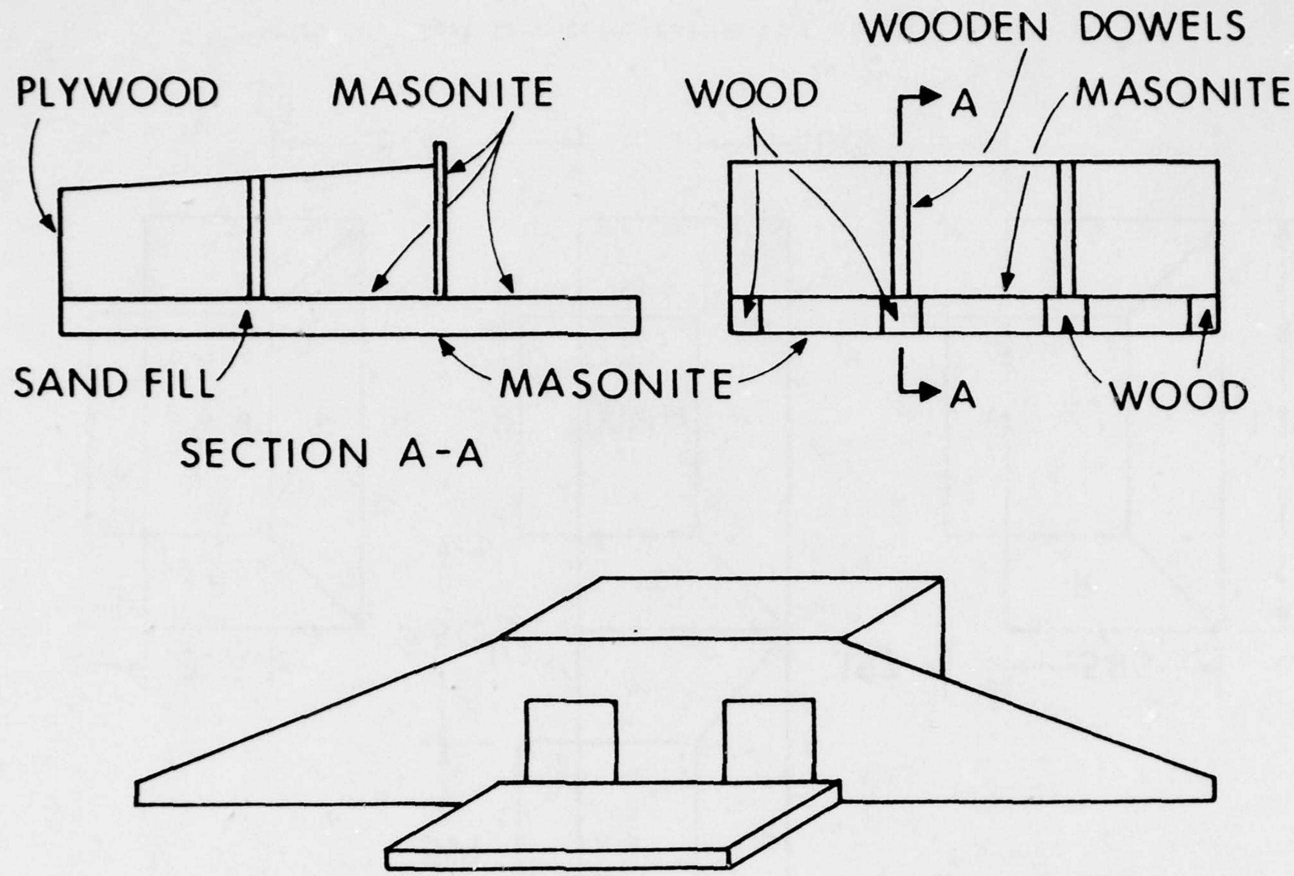

Figure 29. 1/50 Scale ESKIMO VI Donor Model Interior

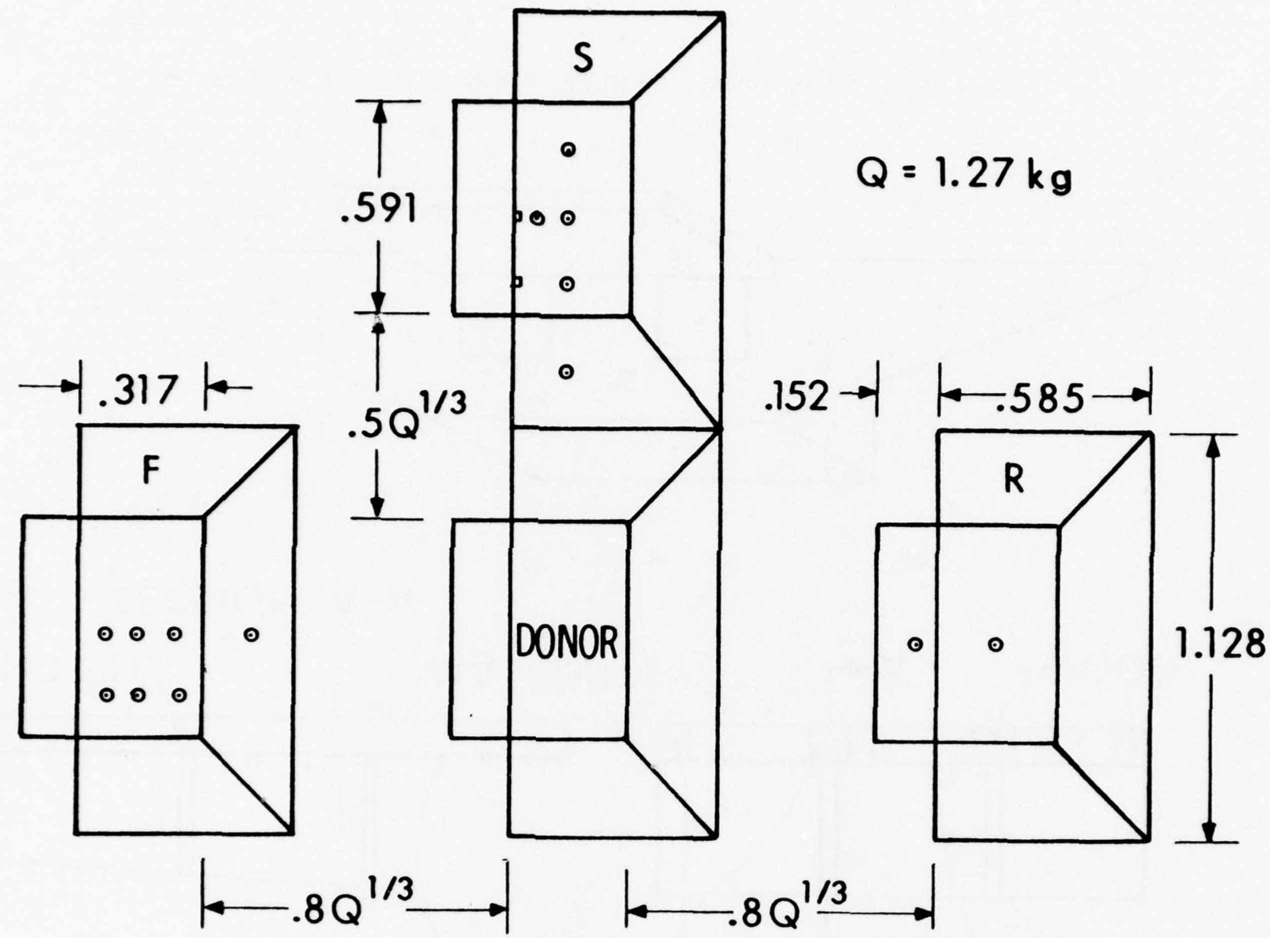

Figure 30. Test Layout for ESKIMO VI Configuration

Impact Sensitivity Testing of Cap-Sensitive Slurry Explosives

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The introduction of cap-sensitive slurries has brought in a remarkable change in technology because they are safer to manufacture and use than nitroglycerine-based high explosives. The high regard for the safety of the slurries and the switch from NG-mixing procedures can lead to problems. This paper presents our attempts at understanding impact sensitivity and finding a realistic measure of the safety of cap-sensitive slurries.

The cap-sensitive slurry made by Canadian Industries Limited (CIL) is based on ethylene glycol mononitrate as the sensitizer, and is marketed under the trade-name POWERMEX.

Extra emphasis on sensitivity testing arose because CIL extended its method of hazard analysis from a qualitative fault free system to full quantification. Mishaps are quantified so that the net fatal accident frequency rate (FAFR) for a process is calculated. Each process must meet a FAFR standard set by the company. As part of the quantification process, a reliable estimate of the probability of initiation of ingredients or explosive is needed when they are subjected to thermal or mechanical stimulus.

In the case of mechanical impact we need to determine initiation probabilities for process-related impacts which are far lower than the range of useful tests

(in the range of probabilities .1 to .9 and usually centered around .5). To extrapolate from test results to much smaller stimulus and probability, we use the statistics of probit analysis (Ref. 1). This implies that one impact parameter (dose) best gives a normal distribution to initiation probabilities.

We have designed and constructed a drop-weight impact test apparatus with the capability of impact sensitivity testing under a variety of impact conditions, and have used the apparatus to determine the probit "dose". The machine has interchangeable drop weights of 5, 10 and 20 kg. which are carried by a bracket running on two vertical rods (Figure 1). On impact, the carrier bracket carries on until stopped independent of the drop weight. A mechanical latch prevents a second impact of drop weight on the target. The target design is much like that at the Swedish Detonics Institute (Ref. 2), a stack of roller bearings (1/2" diameter, 1/2" long) aligned by a set of bushings (Figure 2). The sample is placed beneath the top roller. We have mounted strain gauges on either the bottom or next roller to measure impact duration and pressure. Examples of impact strain measurements are shown in Figure 3 for a) initiation and, b) failure of POWERMEX on sandpaper.

Impact test procedures consist of placing the sample in the target, dropping the weight from a recorded height and registering some degree of reaction of the sample. This reaction usually is qualified to simply detonation (positive) or failure. This procedure is especially useful when trying to determine probabilities of initiation. The decision as to detonation or failure is often left to the subjective senses of smell and sound. We wished to put the decision on a more objective basis by using a gas analyzer (Wilkes Scientific Company

Miran) to detect reaction products, in particular CO. In the apparatus we use, the fraction of infra red light absorbed by the reaction products is called the absorbance. For our tests, an absorbance of .001 is equivalent to a concentration of about 1 ppm of CO, and the limit of detection is about .2 ppm.

It was first assumed that any detectable CO indicated a positive, but this led to inconsistencies such as TNT being more sensitive to impact than RDX or PETN. Also, some explosives, especially oxygen-balanced commercial mixtures, generate less CO than others on reaction. We investigated this problem by measuring CO concentration vs. drop height for several explosives. Unfortunately with a 5 kg. weight dropped from the maximum height (210 cm), no CO was detected for POWERMEX slurries. However tests with the samples consisting of explosive on sandpaper were more conclusive (Figure 4). The resulting curves are similar to those generated by the Rotter test in the United Kingdom (Ref. 3) in which total reaction gas volume is measured. The steepness of the RDX curve compared to the POWERMEX curve at low heights means that initiation probabilities of POWERMEX will be more sensitive to the choice of an arbitrary CO concentration for positives than those for RDX. By comparison of our results of the sensitivity of military explosives with those at the United States Bureau of Mines and Los Alamos Scientific Laboratories an absorbance of .004 was established as the reading above which tests were considered positive.

To determine how the impact parameters changed under various test conditions (number of rollers, drop mass), measurements were made of peak strain and impact duration and compared with the behaviour expected from an elastic impact. The target is considered to be two springs, one with spring constant K_1 representing

the compression (X) of the rollers and the sec ond (K_2) representing the deformation (Y) of the steel surfaces (Figure 5). Mass M strikes the springs with initial velocity V and produces an impact pressure described by a half-sine wave with duration τ and peak pressure σ. The resulting equations for σ and τ are shown in Figure 5.

Measured values of impact duration and peak strain are shown in Tables I and 2 for comparison with the theoretical behaviour. The variation of τ with drop height (independent), drop mass ($\sqrt{M}$) and number of rollers (f(n)) agrees with measured behaviour. The measured strains do not agree as well with the theory but do indicate the occurrence of gross events (Figure 3). Part of this lack of agreement is likely due to non-uniform strain in rollers due to non-planar impact. Presence of sandpaper and/or slurry does not appreciably alter the measured parameters.

We then examined the impact sensitivity of several explosives to observe the effect of varying the impact parameters. The height for 50% initiation (H_{50}), as determined by the Bruceton method is taken as the measure of sensitivity. The results shown in Table 3 show that H_{50} is independent of the number of rollers (i.e. independent of τ) but inversely proportional to the drop mass (Figure 6). Tests performed with four rollers and the 5 kg. drop mass were performed in both series of experiments. Only the results for ANFO do not agree, and this is possibly due to the fact that small amounts were made for each test, and the oil may not have mixed uniformly in one case.

From the above results, it appears that the potential energy MgH is the appropriate dose for the probit analysis of impact sensitivity of explosives on sandpaper. For an accurate probit, probability of initiation at several heights are required, and the method of analysis includes cases where the measured probability is 0 or 1.

The data for POWERMEX 500 (shown in Figure 7) were taken using several batches so that variation in composition is included in the results. The figures in brackets refer to the number of tests producing a probability of zero or one. Other points represent from 10 to 70 drops each. The probit line drawn was determined from the results of almost 1000 drops and gives 50% energy of 16 joules or 33 cm for a 5 kg. drop mass. This intercept agrees with the H_{50} result obtained in the earlier sensitivity tests, but the probit also provides a reliable slope so that estimates may be made of probability at much lower energies. The weakness of the Bruceton test is that it does not give an accurate estimate of the standard deviation (equivalent to the probit slope) of the probability distribution.

Included in Figure 7 are probits determined for powdered RDX and prilled TNT. As expected, the 50% energies agree with the sensitivity measurements, but of extra interest is the fact that the slopes of all three probits are approximately the same. It is possible that powder, prilled and slurry explosives have the same initiation mechanism when impacted on sandpaper. A common slope for all explosives also means that provisional probits may be obtained by the simple Bruceton test until a more precise probit has been determined.

In summary, a new impact machine was built to examine the impact sensitivity of explosives and to provide probit curves for cap sensitive slurries. Results showed that impact-induced decomposition greater than the detectable limit must be used as an indicator of a positive. The measured variation of impact sensitivity with impact parameters suggested kinetic energy to be the correct dose for probit analysis of solid and slurry explosives.

Acknowledgements

This work was performed with the financial support of the National Research Council of Canada Industrial Research Assistance Program.

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1. "Probit Analysis", D. J. Finney, Cambridge University Press, Third Edition, 1971.

2. "Detonics of High Explosives", C.H. Johansson and P. A. Persson, Academic Press, 1970.

3. "The Rotter Apparatus for the Determination of Impact Sensitiveness", H. N. Mortlock and J. Wilby, Explosivstoffe, Vol. 14, p. 49 (1966).

Figures

Figure 1 - General View of CIL IMpact Apparatus.

Figure 2 - Close-up of Target Bearings and Bushings.

Figure 3 - 5 kg. Impact for POWERMEX on Sandpaper.

Figure 4 - Figure of Insensitiveness.

Figure 5 - Elastic Impact on Stack of n Cylinders.

Figure 6 - Dependence of H_{50} on Drop Mass.

Figure 7 - Probit of Impact Sensitivity of Explosives on Sandpaper.

TABLE 1

IMPACT PARAMETERS AT FIXED DROP HEIGHT

H = 25 CM.

# ROLLERS	DROP MASS (KG) 5	10	20
	IMPACT TIME (μs)		
2	370	535	710
3	415	580	815
4	465	635	885
	PEAK STRAIN (ARB.UNITS)		
2	785	1490	2020
3	760	1200	1580
4	770	975	1720

TABLE 2

IMPACT PARAMETERS AT FIXED DROP MASS

M = 5 KG.

# ROLLERS	DROP HEIGHT (CM) 25	50	100
	IMPACT TIME (μS)		
2	370	350	
3	415	400	420
4	465	450	420
	PEAK STRAIN (ARB. UNITS)		
2	784	1100	1620
3	760	1170	1660
4	772	1030	

TABLE 3

IMPACT SENSITIVITY OF EXPLOSIVES ON SANDPAPER

H_{50} (CM) VS. # ROLLERS

M = 5 KG.

# ROLLERS → / H_{50} ↓	H_{50} (CM) 2	3	4
ANFO	25.6 ± .5	25.2 ± .9	25.1 ± 1.1
TNT (PRILL)	15.7 ± .6	20.1 ± 1.4	19.2 ± 2.7
RDX	10.2 ± .3	11.6 ± 1.9	11.1 ± 1.1
SLURRY B	32.9 ± 3.5	36.7 ± 1.3	34.3 ± 1.3

H_{50} (CM) VS. DROP MASS (KG)

4 ROLLERS

M → / H_{50} ↓	5	10	20
RDX	12.3 ± .9	8.9 ± .3	4.6 ± .6
TNT (PRILL)	22.4 ± 1.3	13.4 ± 1.2	6.2 ± .5
ANFO	45.5 ± 2.7	16.4 ± .9	8.7 ± .7
SLURRY A	41.4 ± 9.7	16.2 ± 1.1	8.8 ± 3.3
SLURRY B	41.0 ± 6	19.5 ± 3	9.2 ± .6
SLURRY C	18.3 ± 1.2	10.7 ± 1.1	4.9 ± .3

ERRORS ARE 95% CONFIDENCE LIMITS

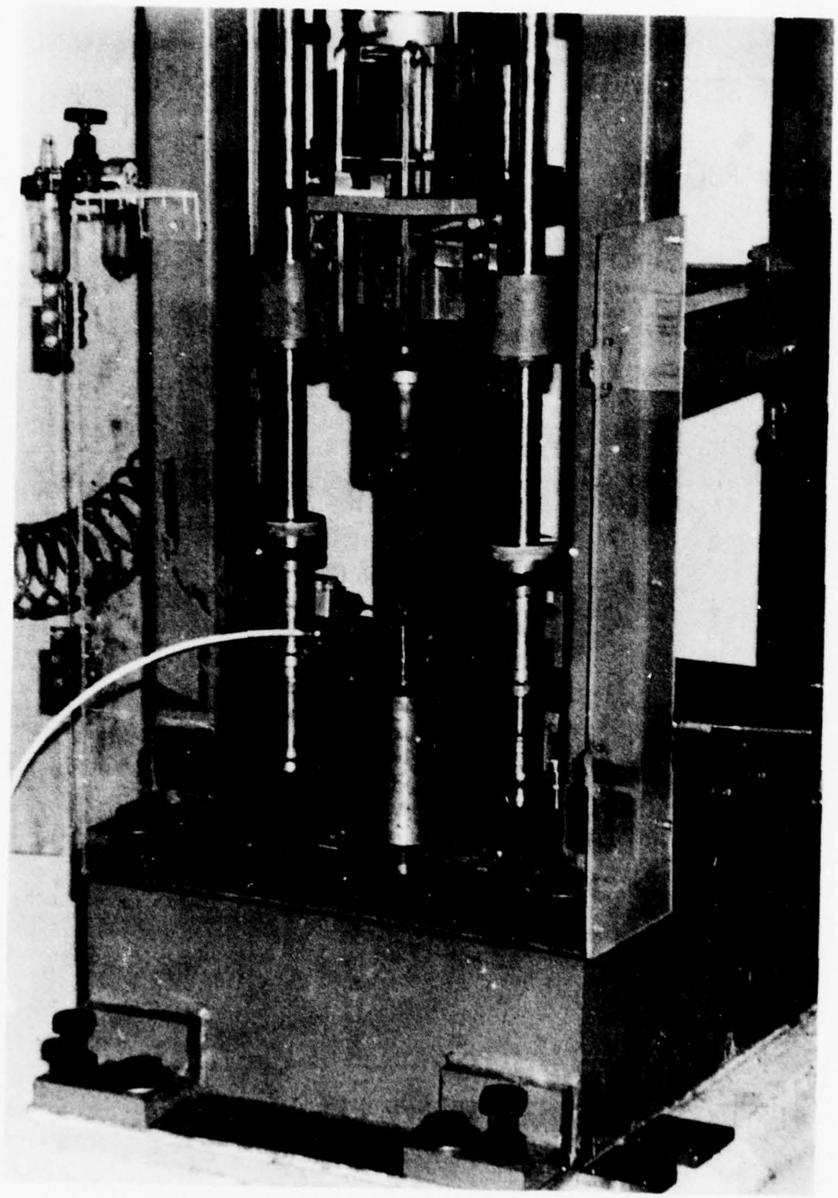


FIGURE 1

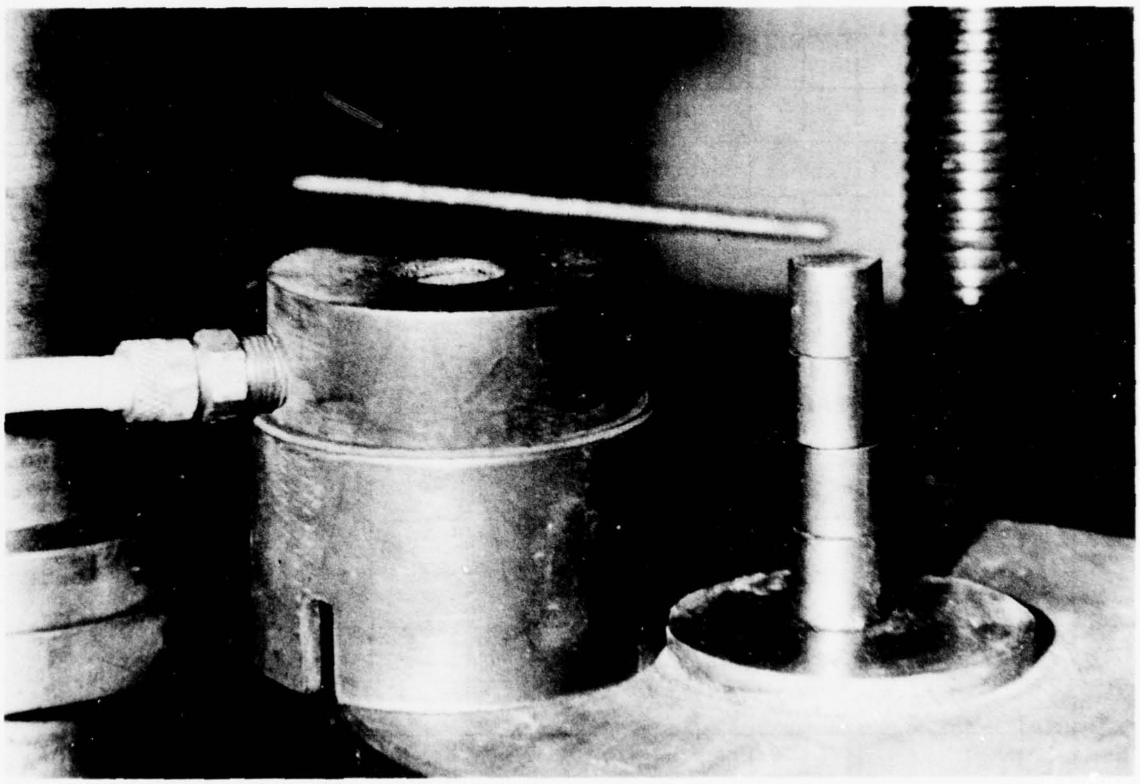


FIGURE 2

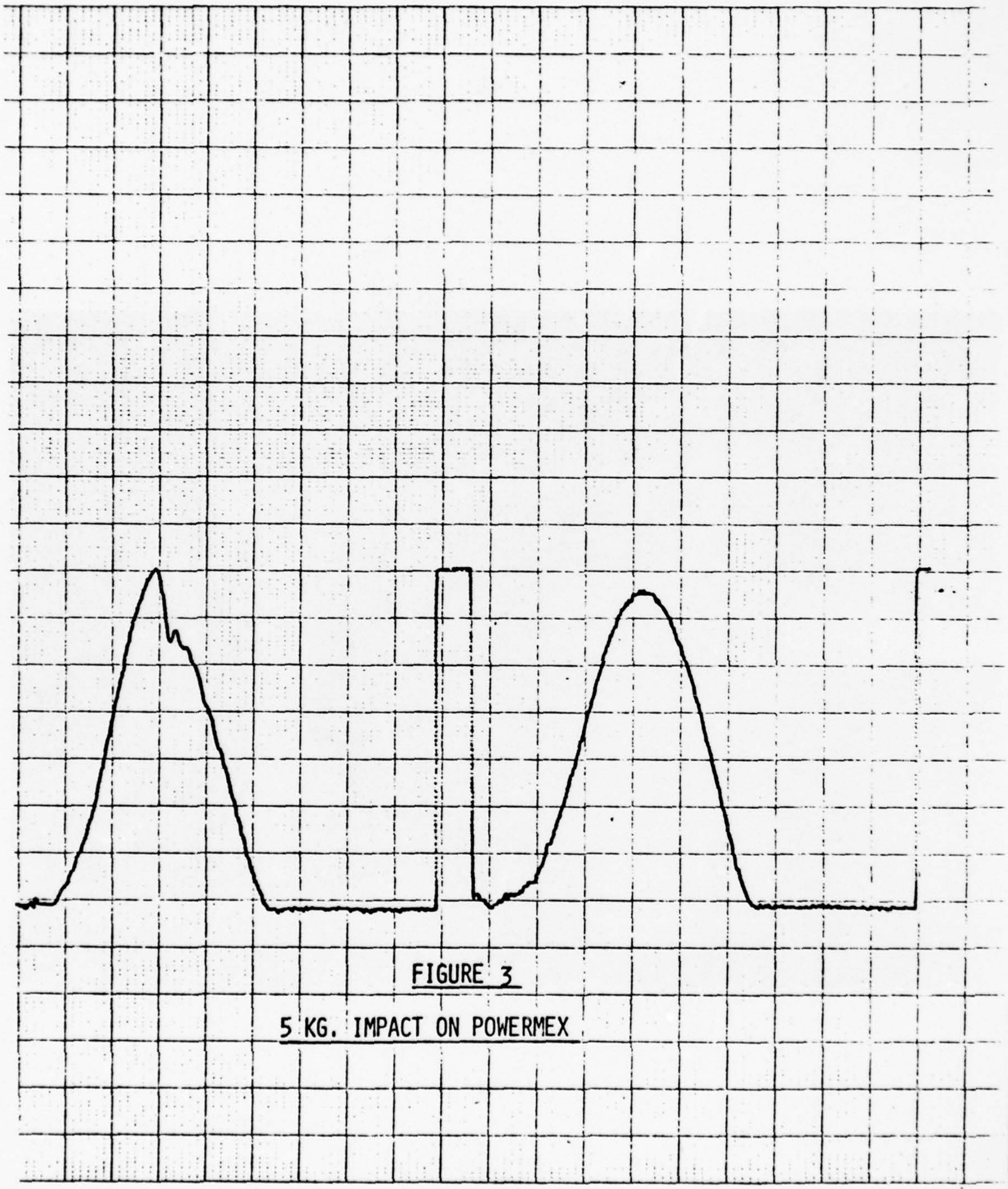


FIGURE 3

5 KG. IMPACT ON POWERMEX

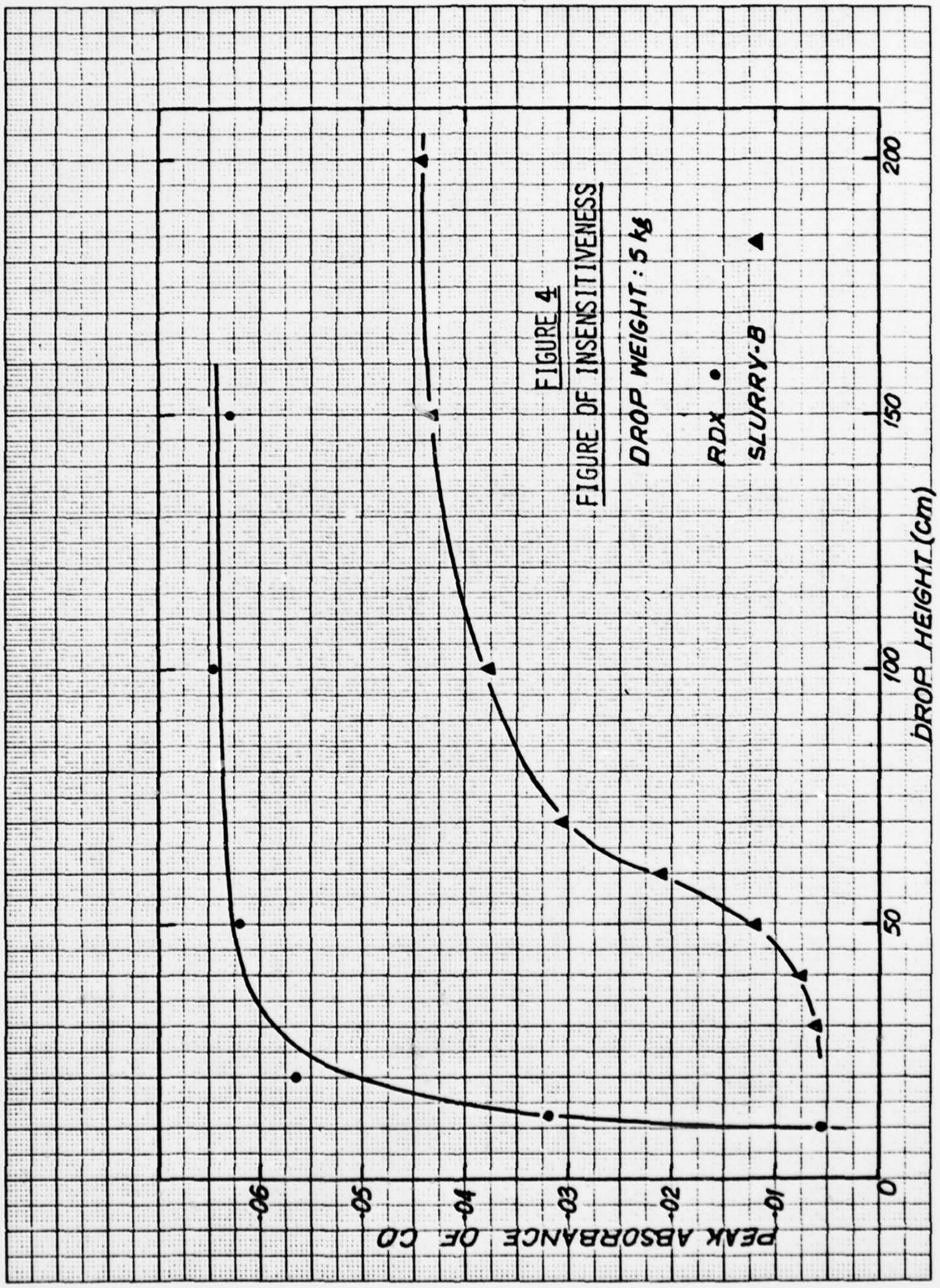
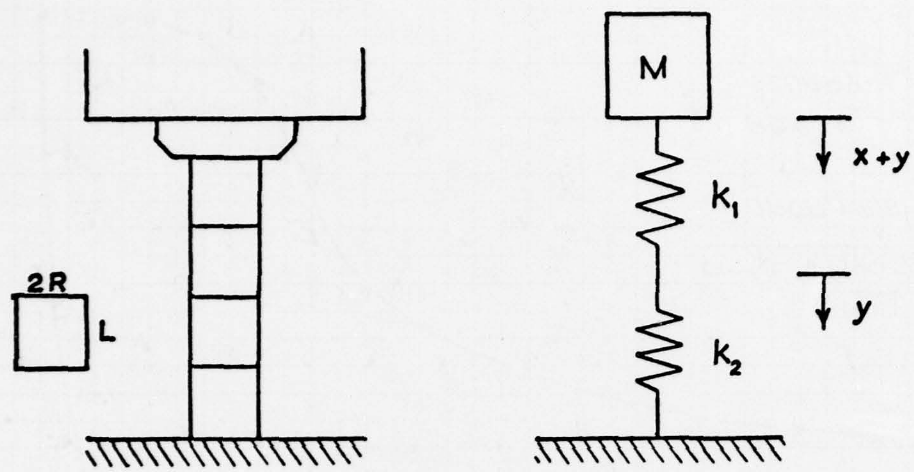


FIGURE 4
FIGURE OF INSENSITIVENESS
DROP WEIGHT : 5 kg
RDX
SLURRY-B
DROP HEIGHT (cm)
PEAK ABSORBANCE OF CO
0
50
100
150
200
.01
.02
.03
.04
.05
.06

46 1510

FIGURE 5



$$\frac{1}{2}MV^2 = \frac{1}{2}K_1 X^2 + \frac{1}{2}K_2 Y^2$$

$$\sigma_{MAX} = V\sqrt{\frac{ME}{\pi R^2 L}} \times F(N)$$

$$\tau = \sqrt{\frac{\pi ML}{R^2 E}} \times \frac{1}{F(N)}$$

$$F(N) = \left[N + \frac{\pi R}{4L}(1-\nu^2)\right]^{-1/2}$$

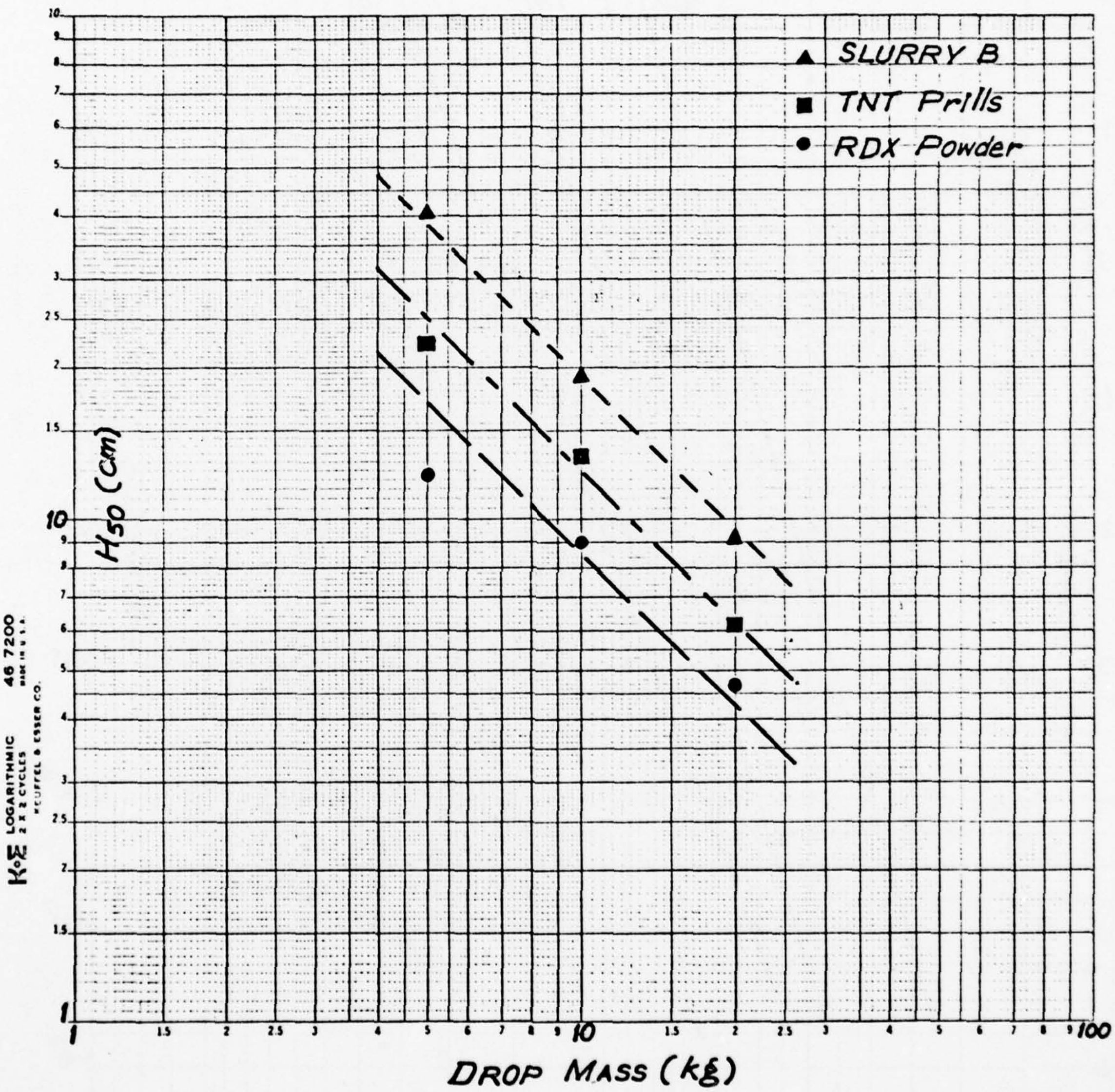
K_1 = ELASTIC CONSTANT OF ROLLERS

$= \frac{\pi R^2 E}{NL}$

K_2 = ELASTIC CONSTANT OF PLANE SURFACES IN CONTACT WITH RIGID PUNCH

$= \frac{4\ RE}{1-\nu^2}$

FIGURE 6



SLURRY B
TNT Prills
RDX Powder
H_{50} (cm)
DROP MASS (kg)
LOGARITHMIC 2 X 2 CYCLES
46 7200
KEUFFEL & ESSER CO.

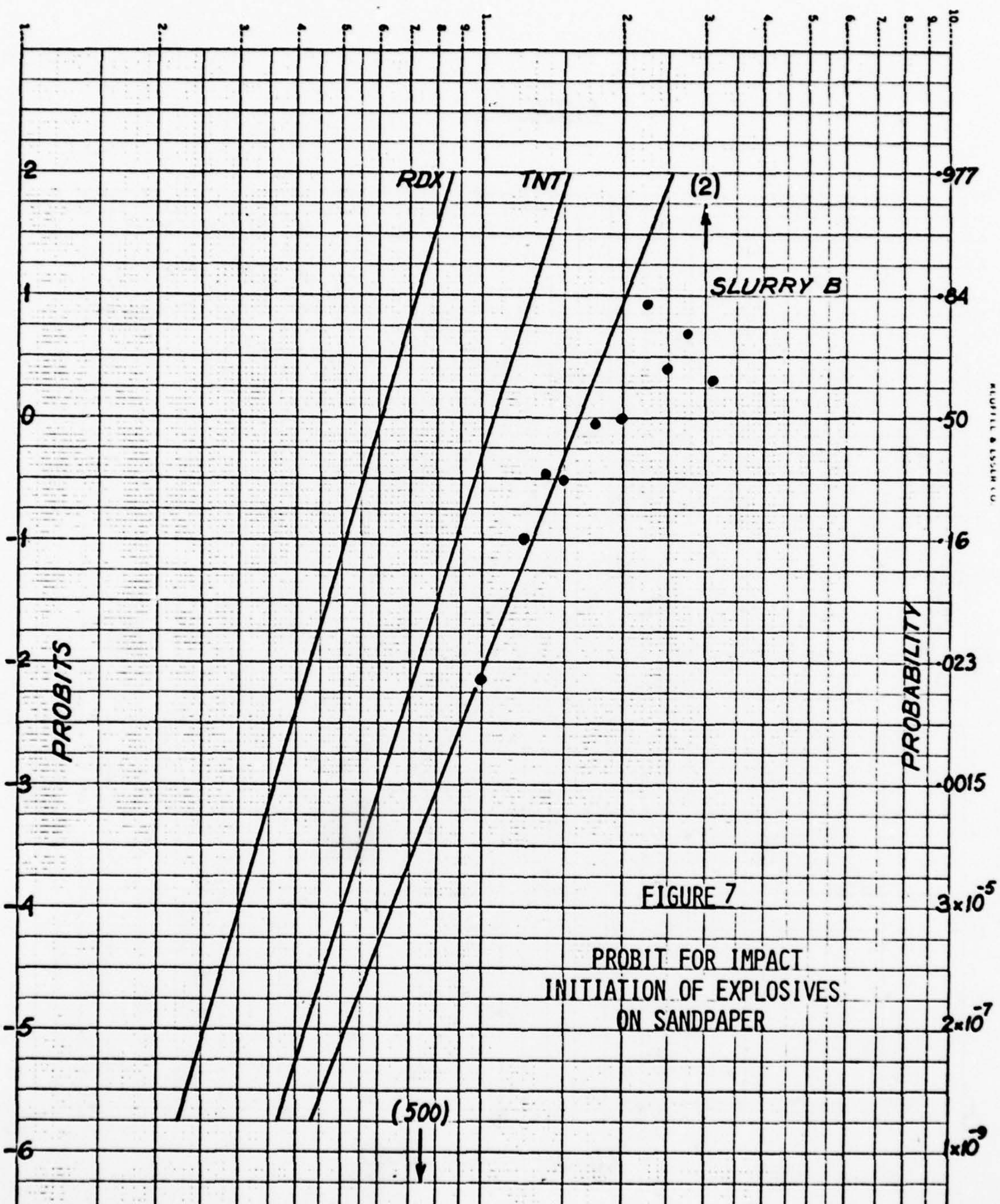


FIGURE 7

PROBIT FOR IMPACT
INITIATION OF EXPLOSIVES
ON SANDPAPER

SOME OBSERVATIONS ON THE PROPOSED DOT TESTS FOR BLASTING AGENTS

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Abstract

The card gap test recommended by the U. S. Department of Transportation for the new Blasting Agent hazard class was compared with several versions of the No. 8 cap sensitivity test. It was concluded that, with a fixed gap and a steel witness plate, the test would not provide any useful information beyond that available from the No. 8 cap test. It was also found that a lead block witness used in the cap sensitivity tests is a more sensitive, and for safety purposes a better, indicator than a detonating cord telltale. For an additional margin of safety, caps with aluminum shells are to be preferred over caps with copper shells.

Introduction

In late 1976, the Department of Transportation published in the Federal Register a proposal for creating a new hazard class to be called Blasting Agents.[1/] This class would include those materials now classi-

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1/ Federal Register, Friday, November 26, 1976, Vol. 41, No. 229.

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fied as nitro-carbo-nitrates and possibly some materials now classified as Propellant Explosives, Class B. The proposed definition of Blasting Agents included eight sensitivity tests to limit the mechanical and

thermal sensitivity of the materials so classified. The mechanical sensitivity tests included a blasting cap sensitivity test, a rifle bullet sensitivity test, an impact sensitivity test, and a card gap test. With the possible exception of the drop weight test, these tests all reflect in varying degrees the shock sensitivity of explosive materials. For example, in a recent paper[2/] it was found that the results

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2/ Watson, R. W., R. L. Brewer, and R. L. McNall. On the Bullet Sensitivity of Commercial Explosives and Blasting Agents. Journal of Hazardous Materials, 1 (1975/76), pp. 129-136.

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of projectile impact tests could be correlated with the results of cap sensitivity measurements in the sense that a projectile velocity could be defined that represents the threshold between cap sensitivity and cap insensitivity. It was also found that under the ordinary conditions of confinement expected in the transport and storage of explosives, materials that were not sensitive to a No. 8 blasting cap were not sensitive to rifle-fired bullets. On the basis of previous experience at the Bureau, which showed good correlation between projectile impact and card gap test results, it was anticipated that the card gap test proposed by the DOT could also be correlated with the cap sensitivity test. For this reason, it was thought desirable to attempt to establish such a correlation in order to judge whether a card gap test was necessary in the proposed classification scheme. In addition, the cap sensitivity test prescribed by the DOT for defining the new blasting agent category differed from that used at the Bureau in that the proposed test utilizes

a detonating cord pigtail instead of a lead block to witness the occurrence of detonation. In view of the possibility that the two different witnesses might lead to different results, the two methods were also compared. The results of these experiments are discussed in this paper.

Experimental Procedures

The experimental arrangement used for the gap test is shown in Figure 1. The test sample is contained in a 16-inch length of cold-drawn seamless mechanical tubing 1.875 inches in outside diameter with a wall thickness of 0.219 inch. The sample is subjected to the shock wave generated by the detonation of a stack of two (2) pressed pentolite pellets, each 2.0 inches in diameter and 1.0 inch thick, weighing 80.5 grams each (density 1.56 grams/cc), initiated by an Army Engineers special (J-2) electric blasting cap. The shock is attenuated by passage through a cylinder of cast acrylic plastic (plexiglass) 2.0 inches in diameter; the length of this cylinder (the gap) controlls the shock amplitude. This arrangement is basically the same as specified by the DOT in reference 1 which was adapted from DOD TB 700-2[3/] with the exception of tube length--16

3/ Explosive Hazard Classification Procedures. Contained in DOD TB-700-2 (May 19, 1967).

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inches versus 5-1/2 inches--and the use of a cut plexiglass gap instead of the stacked 0.01-inch-thick cellulose cards. The tube was lengthened for our experiment in order to assure a long enough buildup to detonation; the use of the plexiglass gap in place of cards is an accepted

procedure and leads to essentially the same results.

Two techniques were used to assess the occurrence of detonation and/or non-detonation. One utilized a 3/8-inch-thick by 6.0-inch-square mild steel witness plate as specified in TB 700-2. The plate was supported 1/16 inch above the end of the test sample using three small (0.5-inch-square) plexiglass spacers; a hole in this plate confirms the occurrence of detonation. The other method used for ascertaining the occurrence of detonation was the Bureau-developed continuous-velocity probe, the use of which is described in references 4 and 5.

4/ Mason, C. M. and E. G. Aiken. Methods for Evaluating Explosives and Hazardous Materials. USBM IC 8541, 1972, 48 pp.

5/ Ribovich, J., R. W. Watson, and F. C. Gibson. *Instrumented Card-Gap Test*. AIAA Journal, Vol. 6, No. 7, July 1968, pp. 1260-63.

Initial experiments with commercial blasting agents showed that the 3/8-inch-thick witness plate was not sufficiently damaged to provide clear evidence of steady versus decaying detonation. However, when the plate thickness was reduced to 1/8 inch, well-defined holes were obtained in the case of steady detonations. This is demonstrated in Figure 2, which shows a detonation and a failure with a 0.375-inch witness plate, and the same with a 0.125-inch witness plate. The explosive used in all four cases was a low-density nitro-carbo-nitrate. The detonations were obtained at a gap of 2.0 inches, and the failures at a gap of 2.25

inches. In all cases, the continuous-rate probe results, which are also provided in Figure 2, agreed with the 0.125-inch witness plate assessment. In view of this, a 1/8-inch-thick steel witness was used in subsequent tests along with the velocity probe.

The version of the cap sensitivity test now used by the Bureau of Mines is shown in figure 3 and consists of a 3-3/8-inch-diameter, 6-3/8-inch-long cardboard container of nominal 1-quart capacity filled with the explosive to be tested; a No. 8 electric blasting cap is imbedded concentrically in the top of the explosive to a depth equal to its length. If the sample is a gel-type material, it is carefully hand-packed to eliminate voids; if it is a free-flowing granular material, it is loaded to the density attained by tapping the container. In both cases, the final densities are reasonably close to the normal shipping densities. This arrangement is set on top of a 2-inch-diameter, 4-inch-long cylinder of common (soft) lead which is in turn supported by a 1-inch-thick, 6-inch-square steel plate. The lead cylinder serves as a witness for detonation: If the block is compressed by 0.125 inch (0.32 cm) or more, the sample is considered to have detonated. The proposed Department of Transportation test is similar except that the witness is a stub of 50-grains/ft detonating cord inserted along a diameter of the container 0.5 inch from the bottom; detonation of the sample is indicated by the detonation of the detonating cord telltale.

The Bureau version of the cap test was run using commercial No. 8 elec-

tric blasting caps with both aluminum shells and copper shells, and the DOT version was run only with the aluminum-shelled caps. Both types of caps had a nominal base load of 0.45 gram of PETN.

Experimental Results

Results of cap and card gap sensitivity tests for 13 explosive materials are presented in table 1, along with the results of the Bureau's projectile impact test, which is described in reference 4. As will be noted, there is a good correlation between the card gap results and the results of the cap sensitivity trials using the lead block witness and caps with aluminum shells. Except for one case (Key No. 1635), explosive materials having critical gaps for detonation of 2.25 inches or less were not cap sensitive, and those having gap values in excess of 2.25 inches were cap sensitive. The blasting agent with Key No. 1635 had produced positive results in previous cap sensitivity trials, as did the low-density NCN with Key No. 1632. In addition, the V_{50} for No. 1635 was somewhat higher than that normally expected for a material of marginal cap sensitivity. These discrepencies have been ascribed to difficulties in maintaining a uniform loading density for these materials.

The cap test results indicate that the lead block witness is a more sensitive indicator than the detonating cord telltale, since in four cases (including the earlier results with Nos. 1632 and 1635) positive results were obtained with the lead block where the detonation cord telltale produced no indications of detonation. This is demonstrated in

figure 4, which shows the results obtained in two tests with a water gel explosive using either the lead block or the detonating cord witness. Other test details, such as explosive loading density, temperature, and blasting cap type, were the same for both trials. As can be seen, the lead witness block was seriously deformed, whereas the detonating cord witness was somewhat damaged but failed to initiate. In a test of another water gel explosive, similar results were obtained when both witnesses were used in the same shot. It can be speculated that the reason for this is that the growth of detonation from a marginal stimulus may be so slow that the detonation pressure has not yet attained a value sufficient to initiate the detonating cord; the deformation of a soft material such as lead would require less pressure, but possibly more impulse. The lead block might also respond to decaying reactions for the same reason.

It may be noted that there were two instances in which positive results were obtained with aluminum shell caps but not with copper shell caps, indicating that the aluminum caps are slightly more effective initiators.

Conclusions

The instrumented version of the DOT gap test correlates very well with the No. 8 cap sensitivity test if the gap criterion used is 2 to 2.25 inches and can provide quantitative information on sensitivity, buildup and/or decay of detonation, and detonation rate. However, if used

without instrumentation and with a fixed gap length, the test would not provide any useful information beyond that available from the No. 8 blasting cap sensitivity test. To provide even this information, the thickness of the witness plate would have to be reduced and the recommended criteria of 70 cards (0.70 inch)[3/] changed.

The lead block witness used in the cap sensitivity tests is a more sensitive, and for safety purposes a better, indicator than the detonating cord telltale. For an additional margin of safety, caps with aluminum shells are to be preferred over caps with copper shells.

Table 1 - Experimental Results

Key No.	Sample	Gap Test (gap values)		No. 8 Cap Sensitivity Test			Bureau Projectile Impact
				Lead Block Witness		Detonating Cord Witness	
		Detonation	No Detonation	Al Shell	Copper Shell	Al Shell	Test V_{50} (m/sec)
X-1910B	ANFO (94/6)	1.75	2	No	No	-	1,275
X-1843	ANFO (94/6)	2	2.25	No	No	No	997
X-1910A	ANFO (94/6)	2	2.25	No	No	-	1,106
X-1655	ANFO (commercial)	2	2.25	No	No	No	914
X-1591	Aluminized ANFO	2	2.25	No	No	No	1,265
X-1697	Low-density NCN	2	2.25	No	No	No	720
X-1633	Aluminized NCN	2	2.25	No	No	No	1,006
X-1696	NCN	2	2.25	No	No	No	1,183
X-1632	Low-density NCN	2	2.25	No/Yes[1]	No/Yes[1]	No	721
X-1635	Metallized ANFO	2.25	2.5	No/Yes[1]	No	No	1,034
--	Experimental mix	2.25	2.5	Yes	No	Yes	618
X-1836	Water gel	2.5	2.75	Yes	Yes	No	700
X-1653	Water gel	2.75	3	Yes	Yes	No	670

[1] Positive results were obtained in earlier tests with these materials.

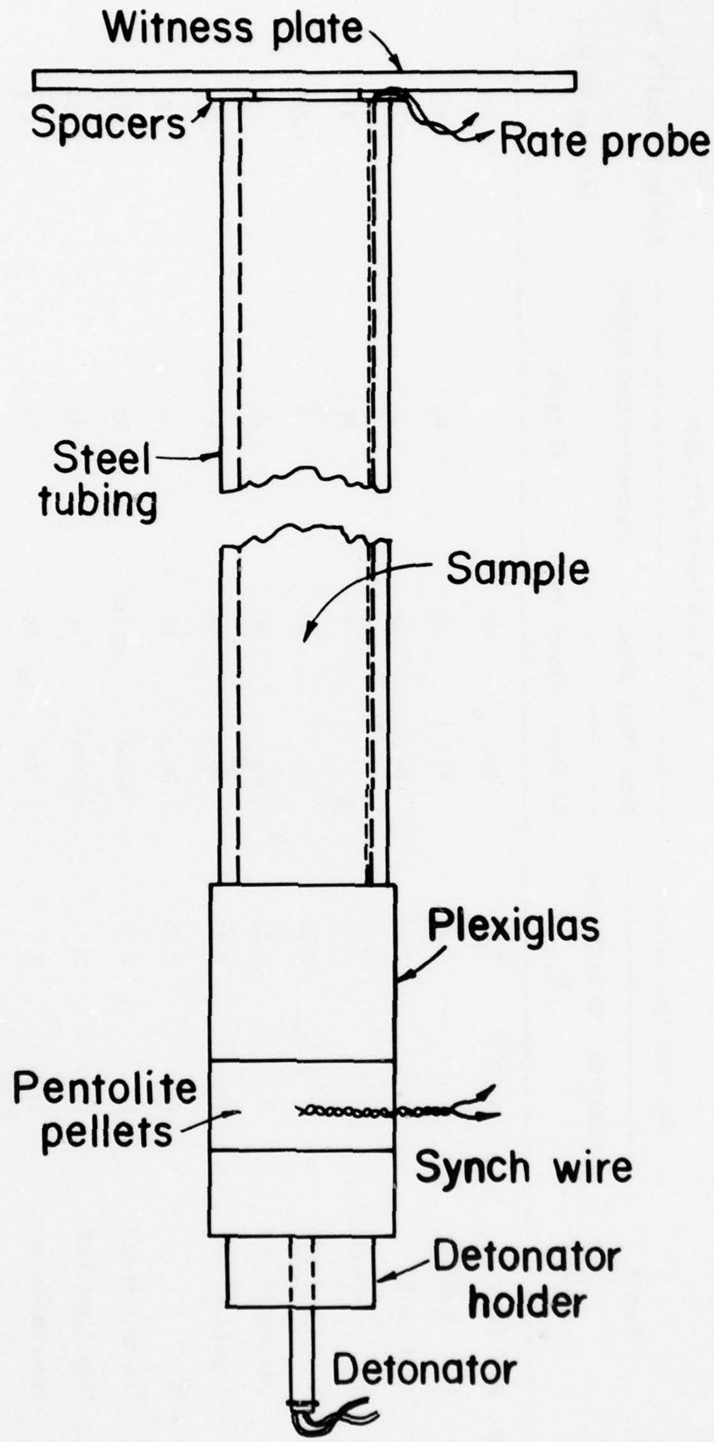

FIG. 1 — EXPERIMENTAL SET-UP FOR THE CARD GAP TEST.

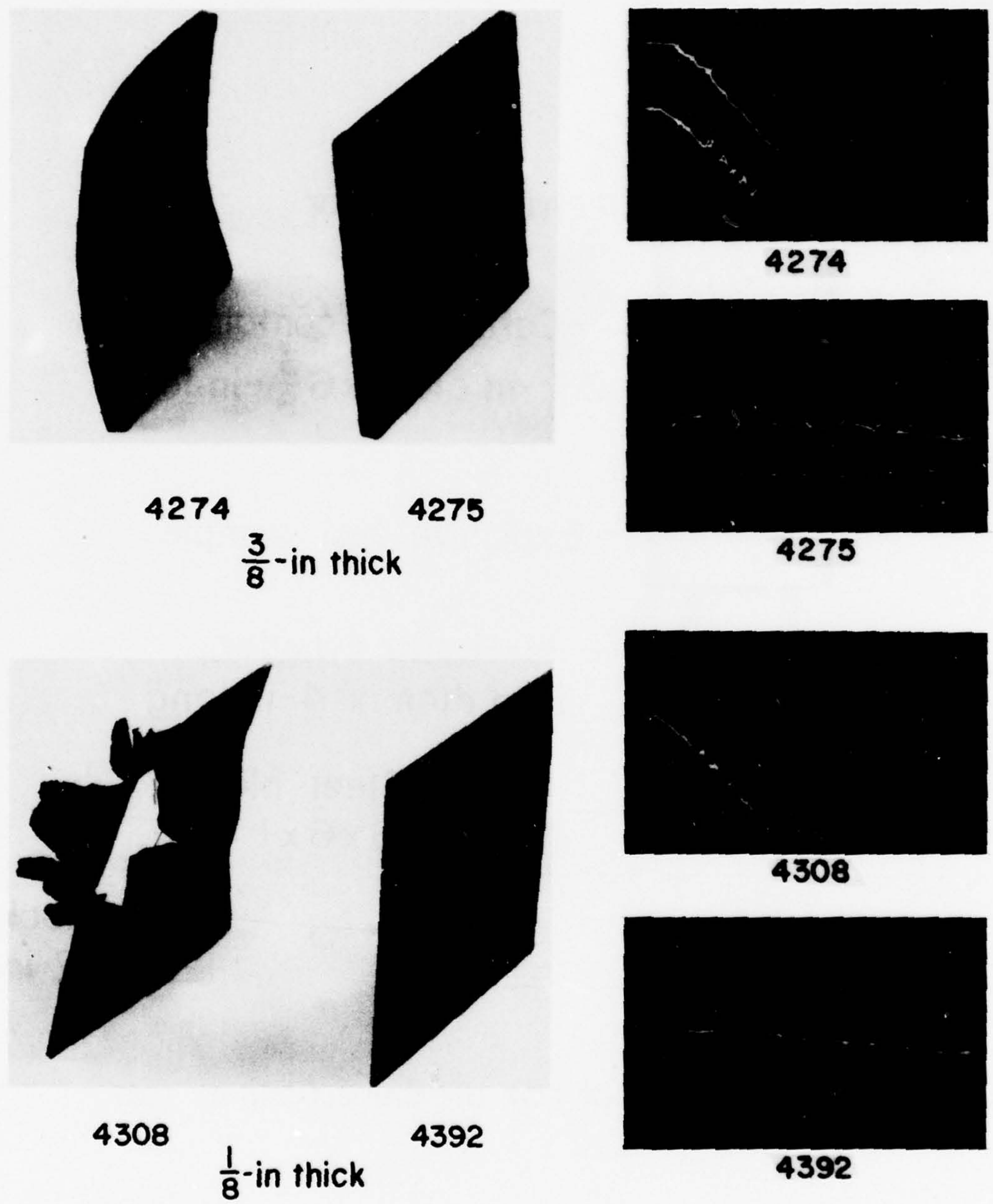

FIG 2 — COMPARISON OF RESULTS WITH A 3/8-IN-THICK AND A 1/8-IN-THICK WITNESS PLATE.

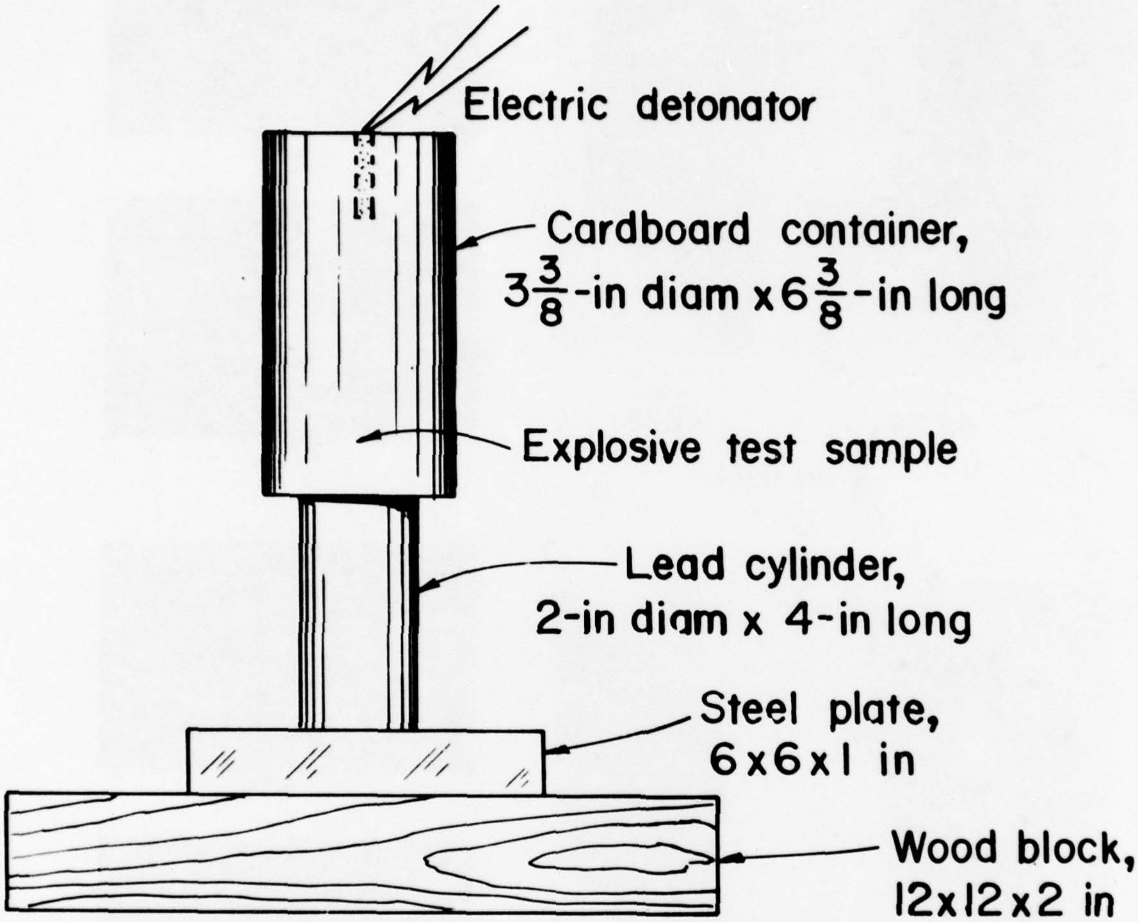

FIG 3 — EXPERIMENTAL SET-UP FOR THE CAP SENSITIVITY TEST

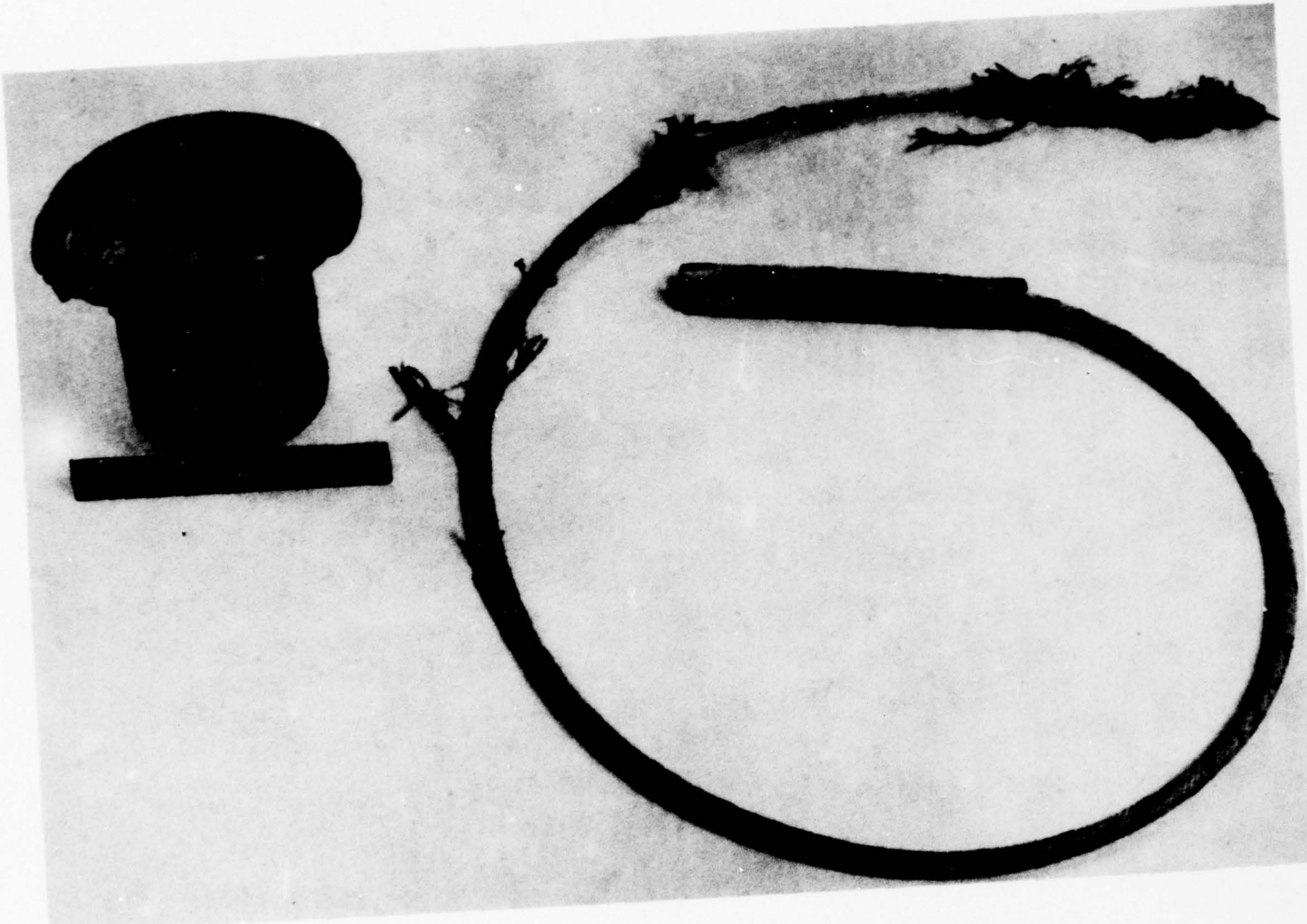

Figure 4 — Comparison of damage to lead witness block with detonating cord tell-tale.

IMPACT INSENSITIVE COMPOSITE EXPLOSIVE

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ABSTRACT

Castable composite explosives (CXs) based on RDX in a hydroxyl-terminated polybutadiene binder have been developed and examined with a view to their possible use in Service munitions. The advantageous properties of CXs include: No volume change during cure, no exudation or deterioration at high temperature, high resistance to thermal and mechanical shock, high resistance to dusting, good adhesion to most containing walls, insensitive to impact-friction, etc. In measuring some of these properties, no deterioration or initiation could be detected under the most extreme conditions to which the CX was subjected.

1.0 INTRODUCTION

A continuing project was undertaken at DREV several years ago to investigate the production, properties and uses of a relatively new type of high explosive, which consists of one or more energetic ingredients supported by a fluid (called the binder) that solidifies upon polymerization. A curable plastic bonded explosive of this type is called a castable composite explosive (CX). This paper describes the general characteristics of some of these CXs and their potential applications in Ordnance stores.

The disadvantageous features of conventional Service high explosives are well known. In general they lack mechanical strength and are brittle, hence they are subject to cracking as a result of thermal or mechanical shock. Any cracked filling is potentially hazardous because part of the filling may shift and be ignited by friction, especially if a crack has opened up so as to make a space in which explosive dust may accumulate, finely divided explosive being more sensitive to ignition by any one of several types of stimulus. Premature ignition may occur also if there is an incomplete fill such as a base separation, a condition very difficult to avoid with certainty for those explosives which are cast in place and shrink upon soldification, such as all TNT-based filling. Prematures during launch as a result of ignition at a cavity have been discussed by Pasman (1). In addition, conventional cast explosives are subject to porosity, which renders the filling more sensitive, and for those which are based on TNT there is the further risk of exudation as well as the limitation that they can be used only for applications in which the temperature remains at all times below the melting point of the filling.

On the other hand CXs are non-remeltable, since polymerization is non-reversible, hence they can be subjected to temperatures as high as their components can sustain. But some other advantages imputed to CXs stood in need of verification and quantization, to assess the extent of any potential gain from their use. Further, any unfavorable feature of a CX formulation should be detected and assessed at an early stage in its consideration. With these ends in view, CXs were examined with respect to their thermal, mechanical and explosive properties and for their ease of preparation and loading into high performance shell.

2.0 EXPLOSIVE PREPARATION AND PROJECTILE LOADING

2.1 Composition

The composition of a typical CX formulation is given in Table I. RDX, the sole energetic ingredient in CX-84, was obtained from Canadian Industries Limited in two forms, designated Class E Type B and Class C Type B. Both are covered by the military specification

RDX MIL-P-398C. The former consists mainly of fine crystals and was used 'as received'. The latter was also sometimes used 'as received', but when the crystal distribution was on the fine side of the specification the fine fraction passing through a 65 mesh tyler sieve was discarded.

Other CXs investigated contained energetic ingredients other than RDX alone. These included HMX, AP and aluminium.

At the beginning of these studies, the binder used in the CX formulation consisted of hydroxyl-terminated polybutadiene prepolymer (R-45M) produced by Arco Chemical Company but because of availability R-45HT is now used. Diotcyladipate (DOA) as a plasticizer is used at a concentration of about 35% of the binder formulation. An antioxidant 2,2'-methylbis(4-methyl-6-terbutyl phenol) (A-2246) is included in the R-45HT at a concentration of 0.25%. A curing agent 2,4-toluene diisocyanate is used at a concentration to make the ratio (NCO)/(OH) lie between 0.95 to 1.1. Most of our CX formulations also contain minor ingredients in an amount of approximately 0.02%.

2.2 Processing

The process for the production of the CX on a pilot plant scale could be divided into three stages as shown in Figs. 1 and 2: RDX phlegmatizing; mixing and casting; and curing.

a) RDX phlegmatizing

This operation is performed in a 10-gal planetary mixer. A certain quantity of polybutadiene R-45HT and ethyl alcohol are first introduced, then the ethanol-wet Classes E and C RDX crystals are added, followed by the minor ingredients. The mixer is then operated at room temperature for 30 min which is sufficient to ensure diffusion of the minor ingredients and the breakup of agglomerated particles. Next the temperature of the mix is increased to 70°C and the pressure reduced to about 2 Torr, then the mixer is operated for an additional 2.5 h for removing the ethyl alcohol.

b) Mixing and casting

This operation is performed in a helicone vertical mixer, capacity 10 gal, Model 10CV, manufactured by Atlantic Research Corporation. The liquid ingredients such as the dioctyladipate and the fraction of R-45HT necessary but not already on the RDX crystals are first introduced into the mixer. The phlegmatized RDX is then introduced by a screw type feeder and mixed for 30 minutes at 60°C and for an additional

2 h under a pressure of about 5 Torr. After this mixing cycle the curing agent, toluene diisocyanate, is added and dispersed in the mass by mixing for an additional 30 min. Finally the composition is transferred directly, by gravity and under vacuum, still a temperature of 60°C, into casting molds or Service shell.

c) Curing

The filled molds or Service shell are transferred into an oven heated at 60°C and the CX polymerized or cured at atmospheric pressure for 1 to 4 days.

Some typical processing characteristics are given in Table II. The processing of CX with solids loading exceeding 85% by weight requires generally the use of special measures to control the ingredient crystal sizes. Casting viscosity usually does not exceed 10 kP but before the addition of the TDI the viscosity could be near to 20 kP.

Little difficulty was experienced in controlling the pot-life, defined as the interval after adding the curing agent up to appearance of an appreciable rate of viscosity increase. The pot-life of each formulation is measured by taking a sample from the mixer at the end of the mixing cycle and maintaining it at the mixing temperature while it is tested in a modified recording Haake Rotoviscometer. Pot-life ranged from 2 to 6 hours, any of which is considered adequate.

The extent of any volume change during polymerization is of interest for almost any Service application. No evidence of any change in volume was detected.

2.3 Filling of projectiles

Several 3"/70 projectiles were loaded with CX compositions based on R-45M to develop techniques which yield adequate fillings and to produce filled shell for use in environmental and performance trials. They were loaded directly from a 0.5-gal helicone vertical mixer under vacuum using gravity flow, the shell being vibrated to ensure completeness of fill. Each shell was initially overfilled and then most of the excess removed manually using a special spatula designed to empty it down to a fixed distance below the end of the shell body. Next the fuze cavity mold was screwed under vacuum into the threaded nose of the shell, forcing out the remaining excess via overflow holes as illustrated in Fig. 3. The filled shells were cured at 60°C for about 6 days. It is expected that this filling technique could be adapted for production loading.

Each projectile was prepared for loading with CX by treating its interior so that the filling would adhere only to selected areas of the shell. Initial attempts to load projectiles produced fillings with many fine cracks detected by X-Rays, attributed to tensile failure as a cured filling shrinks more than a shell body upon being cooled below the curing temperature. To prevent the development of shrinkage cracks, an appreciable portion of the shell interior was treated with a suitable dry release agent so that the explosive would not adhere to those areas.

The ability of CX-loaded shell to withstand thermal and mechanical shock was investigated, for possible deterioration of the CX, by X-raying in two orthogonal views. Projectiles were subjected to cycles between -40 and 60°C. No defect was detected in these fillings, neither before nor after cycling.

3.0 MECHANICAL AND EXPLOSIVE PROPERTIES

3.1 Mechanical and thermophysical properties

The mechanical properties of CX compositions were systematically measured at -50, 20 and 60°C using JANAF diecut dogbone specimens on an Instron tester operating at an extension rate of 2 in/min; the thermophysical properties (specific heat, coefficient of linear thermal expansion and thermal conductivity) have been reported by Christie and Drolet (2) for several CX formulations. Some of these properties for a CX containing 85 or 84% of RDX at 20°C are given in Table III which gives also comparable values for Composition B. In can be seen that the elongation of CX-85 at maximum strength is about 20% compared to 0.1% for Composition B, strength being respectively 500 and 1200 kPa. The coefficient of thermal expansion of CX-85 is about double that of Composition B. Measurements made at -50°C show that the low temperature mechanical properties of CX are superior to those found at room temperature.

3.2 Chemical and physical stability

Chemical and physical stability of CXs have been studied by different methods on samples submitted to accelerated aging (3). It was found that all our CXs aged well. Gas evolution under a vacuum stability test (a 5-g sample held at 100°C for 48 h) is less than 1.2 cm^3. The time change of elongation at maximum load was found to fit well the empirical equation.

$$\varepsilon_o/\varepsilon = kt^{0.5}$$

where ε_o and ε are the elongation at maximum strength at time 0 and time t of aging, k being a rate constant at any given temperature.

3.3 Explosive sensitiveness

Sensitivity to shock was measured by the DREV Gap Sensitivity Test (Fig. 4) using specimens 1.25 x 1.25 x 3 in; the donor is tetryl (D = 0.62 in, L = 1.36 in) and the gap is aluminium. In these tests all 'no-goes' with CX left a short residual portion of CX adhering to the steel witness plate. As indicated in Table IV the sensitivity of CX-85 was found to be comparable to that of Composition B.

Sensitivity to friction-plus-impact was assessed by the AWRE Skid Test (4) using hemispherical specimens of diameter 14 in, a drop height of 40 feet and an impact angle of 76° from the vertical. In this test the explosive hemisphere is suspended between 2 utility poles in such a manner that during lift and after release it always has its flat face horizontal. Sixteen CX tests were conducted, of which 10 were CX-85 while the remaining 6 also included AP and/or aluminium in their formulation. In each test the hemisphere was undamaged except for an elliptical scar about 4 x 7 in on its spherical surface. This scar was bright yellow in color, fading over the course of a few hours to that of the original surface. A similar patch of yellow was imprinted onto each target. There was no evidence of explosive ignition in any test. This non-ignition was confirmed in about half the test drops for each of which a ciné record was obtained. Each ciné film shows a small cloud emanating from the point of impact but a similar cloud was produced when the hemisphere was an inert composite. Composition B is reported to react when released from a height of 10 ft if it impacts upon the target at an angle of 45°, the latter impact angle being a less severe test condition (4).

Sensitivity to bullet impact was measured by the Picatinny Rifle Bullet Impact Test. In this test the CX is loaded directly into a threaded 3-in length of 2-in ID pipe, wall thickness 1/8, closed at one end. The pipe is then closed at the other end by screwing on a threaded cap, inevitably leaving a small air space. A single shot of 7.62-mm Ball C-21 ammunition is fired (nominal speed 2700 ft/s) so as to enter the pipe at the center of the nipple while travelling perpendicular to its axis of symmetry. The results for CX-84 are given in Table IV. It can be seen that no violent reaction was detected with CX-84 but it burned in 50% of the cases, whereas violent reactions occur for TNT, Comp B and H-6.

3.4 Explosive output

Our CXs were assessed with respect to their ability to accelerate fragments using the Standard Cylinder Test (5). In this test a long 2-in-diameter cylinder of explosive is detonated within a close-fitting copper sleeve having a 0.204-in-thick wall, while the wall expansion is being monitored by a streak camera. The velocity attained

by this wall at the moment when the tube OD has expanded by 76 mm is a measure of the velocity which would be given by the explosive to side-projected fragments from a munition. This test indicated that fragment kinetic energy for CX-85 would be 14% lower than for Composition B (6).

4.0 CONCLUSIONS

A continuing experimental program has pointed up some of the advantages and one disadvantage of using castable composite explosives in standard Service shell. The energy given to shell fragments by an RDX composition containing 85% of RDX is about 14% less than for Composition B. In paying this penalty the user attains important advantages over TNT-based explosives: no exudation, no shrinkage cavity, high resistance to thermal and mechanical shock, high resistance to dusting, non-remeltability, high adhesion to shell wall, insensitiveness to friction, etc.

In Canada, no Ordnance stores are actually filled with composite explosives. However, one formulation is being tested in preproduction quantity in two different types of warhead under development.

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TABLE I

TYPICAL CX FORMULATION

INGREDIENTS	WEIGHT PERCENT	
FINE RDX (CLASS E)	25.3	84% SOLIDS
COARSE RDX (CLASS C)	58.7	
POLYBUTADIENE (R-45HT)	9.66	16% LIQUIDS
DIOCTYLADIPATE (DOA)	5.60	
TOLUENE DIISOCYANATE (TDI)	0.74	
MINOR INGREDIENTS (ADDED)	0.02	

TABLE II

CX PROCESSING CHARACTERISTICS

SOLIDS INGREDIENTS (%)	80 TO 89
VACUUM (TORR)	1 TO 10
TEMPERATURE (^{O}C)	60
VISCOSITY (KP)	1 TO 20
POT LIFE (HOURS)	2 TO 6
CURING TIME AT 60^{O}C (DAYS)	1 TO 4

TABLE III

TYPICAL CX COMPARED WITH COMPOSITION B

PROPERTIES AT 20°C	CX-85	COMP B
DENSITY (G/CM^3)	1.56	1.68
HARDNESS (SHORE "A")	30 TO 75	----
ELONGATION (%)	20	0.1
TENSILE STRENGTH (KPA)	500	1200
COEF. OF THERMAL EXPANSION (/°C)	11×10^{-5}	6×10^{-5}
VELOCITY OF DETONATION (M/S)	7900	7750
RELATIVE FRAGMENT ENERGY (TNT = 75 1/2)	86	100

TABLE IV

SENSITIVENESS TO SHOCK AND BULLET IMPACT OF A TYPICAL COMPOSITE EXPLOSIVE: COMPARISON WITH SERVICE EXPLOSIVES

EXPLOSIVE	PICATINNY RIFLE BULLET IMPACT TEST				DREV GAP TEST
	EXPLODED (%)	PARTIAL (%)	BURNED (%)	UNAFFECTED (%)	(INCHES OF ALUMINIUM)
CX-84	0	0	50	50	0.49
TNT, CAST*	2	1	1	96	<0
COMP B, CAST*	3	13	4	80	0.45
H-6 *	80	0	0	20	0.38

* RESULTS FROM PICATINNY ARSENAL

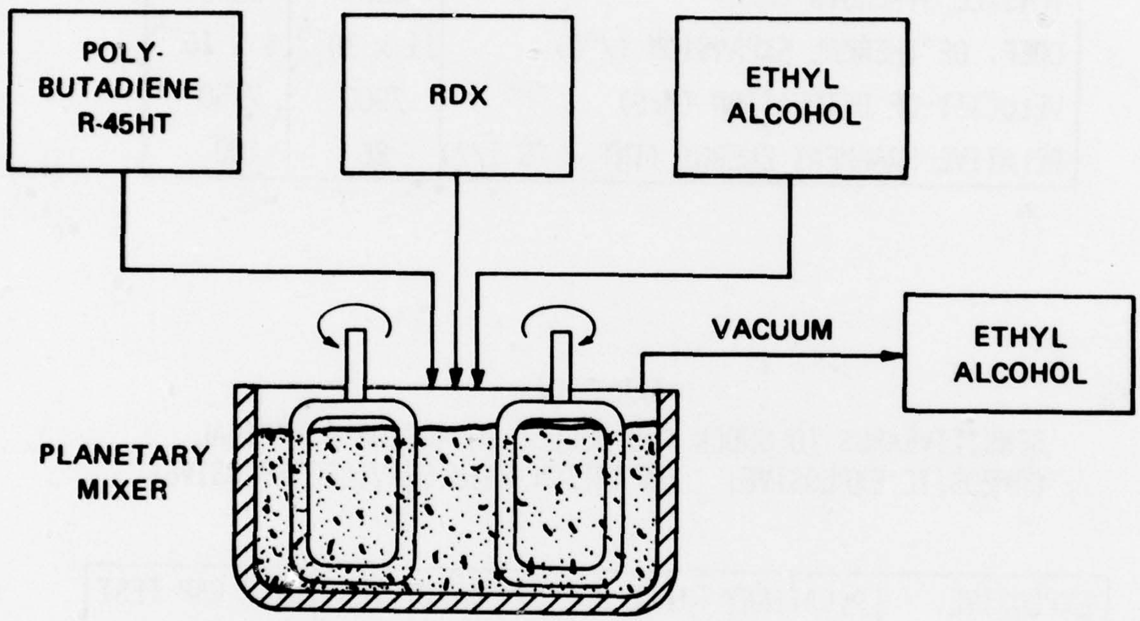

FIG. 1 - PHLEGMATIZING RDX

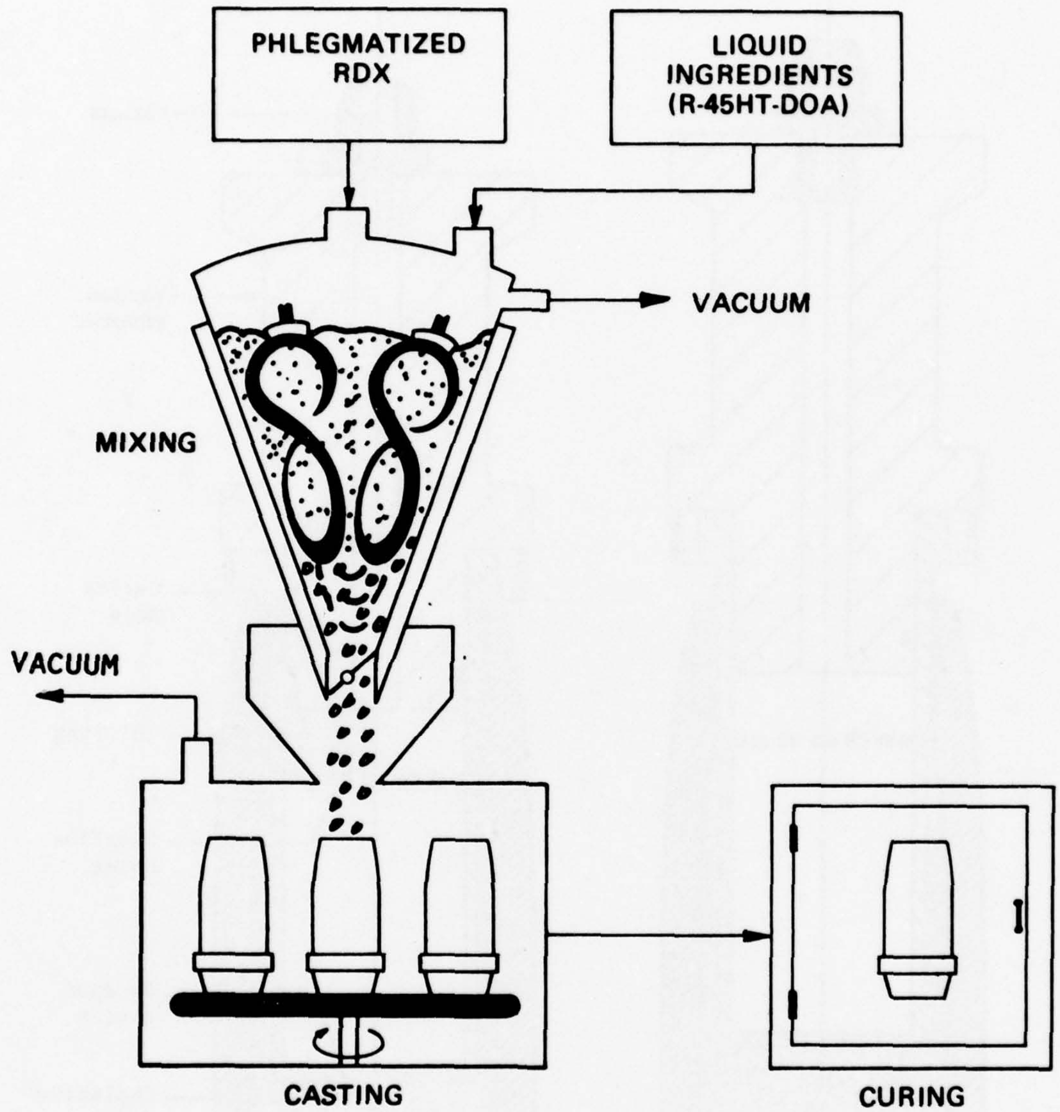

FIG. 2 - PROCESSING CX

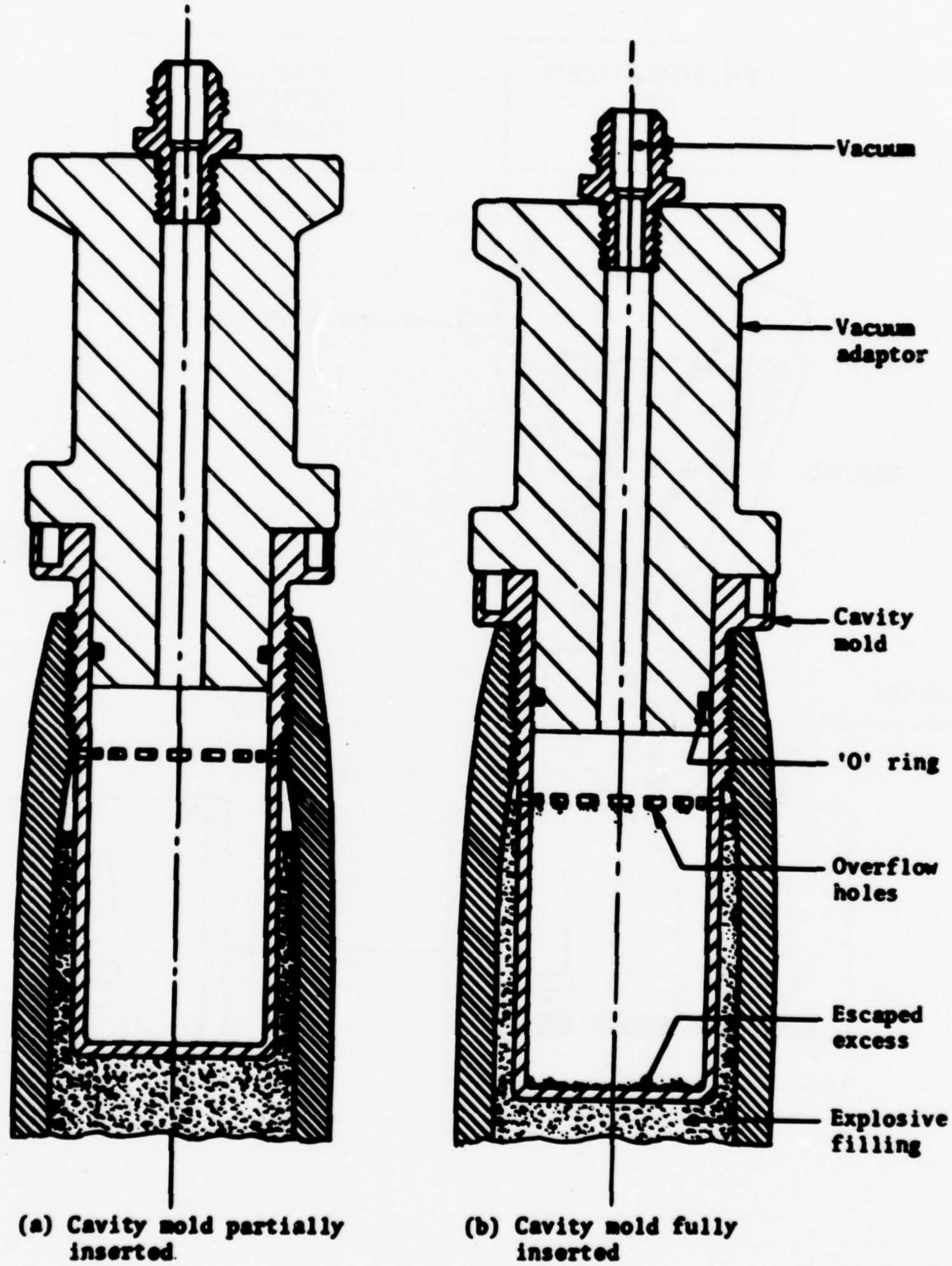

FIG. 3 - LOADING CX INTO A 3"/50 SHELL

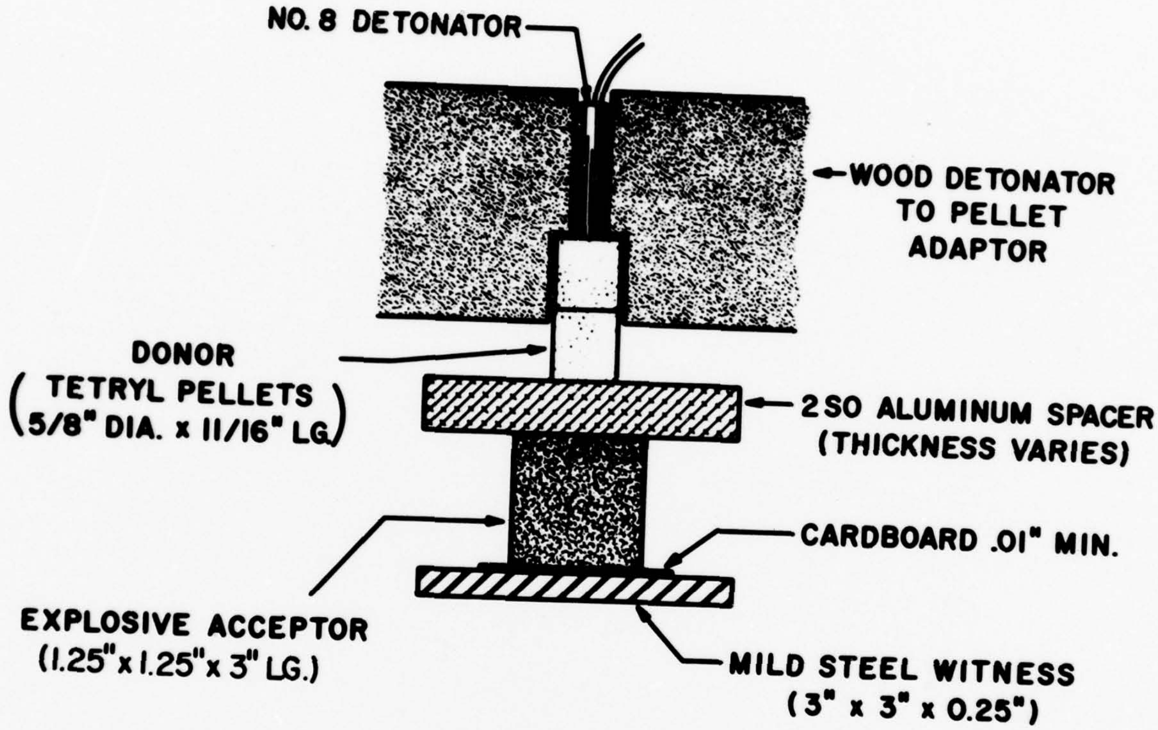

FIG. 4 - DREV GAP SENSITIVITY TEST

BLAST MEASUREMENTS AT CLOSE STANDOFF DISTANCES
FOR VARIOUS EXPLOSIVE GEOMETRIES

by

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ABSTRACT

This paper describes the results and techniques of a 75-shot test program designed to expand the blast technology of pressure and impulse at small scaled distances 0.12 to 1.2 m/kg$^{1/3}$ (0.3 to 3.0 ft/lb$_m$$^{1/3}$). A model analysis was developed to design scaled experiments to generate these data. Pressure bars, piezoelectric transducers and impulse plugs were used to measure the blast parameters of spheres, cylinders and cubical shapes of explosive charges. The explosive used was Pentolite and Composition C-4. These charges were suspended above an infinite reflective surface,and blast measurements were made directly below the charge and at slant ranges. Plots of peak reflected pressures and scaled impulse distances are presented and compared with work done by other investigators.

INTRODUCTION

This report describes an experimental program conducted by Southwest Research Institute (SwRI) for the U. S. Army Armament R & D Command, Dover, New Jersey, under Contract DAAA21-76-C-0219. The objectives of this program were:

- to expand blast technology of pressure and impulse versus scaled distance into the region of small scaled distances of 0.12 to 1.2 $m/kg^{1/3}$ (0.3 to 3.0 $ft/lb_m^{1/3}$), and
- to investigate the effect of charge shape on blast output at small scaled distances.

As part of the Army Plant Modernization Program, measured air blast parameters, such as pressure and impulse, have been accumulated for a variety of explosives, propellants and pyrotechnics in their in-process and final product configurations. The results so obtained are subsequently utilized in the design of structural walls for the modernization program. A requirement for blast parameters at small scaled distances of 0.12 to 1.2 $m/kg^{1/3}$ (0.3 to 3.0 $ft/lb_m^{1/3}$) existed prior to initiation of this test program.

The transducers chosen to measure peak blast pressures were pressure bar gages [(1)*] which were designed, developed, fabricated and calibrated at SwRI and other various commercially available piezoelectric pressure transducers. The type of pressure transducer used depended upon the peak expected pressure, the pressure bars being used for the higher expected pressures up to 2,100 MPa (300,000 psi).

Two methods were used to measure specific impulse. One method was to integrate the pressure-time trace produced from the output of the pressure transducers. This was practicable for some of the traces from the piezoelectric transducers but not from the pressure bar transducers. The other method used was the plug technique developed by the Ballistic Research Laboratories (BRL) for measuring blast impulses.[(2)] A more detailed discussion of this technique and description of the pressure measurement systems used are discussed in the following sections.

The peak pressure and specific impulse data were obtained from 13 tests involving Pentolite spheres, 32 tests involving cubes of

Composition C-4 explosive and 30 tests involving cylinders of composition C-4 explosive. The Pentolite spheres were cast explosive charges while the C-4 charges were carefully formed by hand with appropriate forming tools. These test charges were suspended at scaled distances varying from 0.12 to 1.2 $m/kg^{1/3}$ (0.3 to 3.0 $ft/lb_m^{1/3}$) above the test platform and were initiated with an exploding bridgewire detonator. In an effort to save time and money, all tests were conducted in scaled model size with the charge weights varying from 0.0567 to 0.680 kg (0.125 to 1.5 lb_m).

In this paper, a technical discussion is given covering the model law used to design the experiments. The experimental program outlines the overall test program, experimental set-up, the techniques used for measuring pressure and impulse and the approach to the data reduction. The results and analyses are presented in the form of graphs, tables and illustrations. Conclusions and recommendations are made.

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*Superscript numbers in parenthesis identify the references given at the end of this paper.

TECHNICAL DISCUSSION

Experimental studies of blast wave phenomena are often quite difficult and expensive, particularly when conducted on a large scale. Methods of computation of blast wave characteristics are often so involved that one cannot economically repeat these computations while varying, in a systematic manner, all of the physical parameters which may affect the blast wave. So, almost from the outset of scientific and engineering studies of air blast, various investigators have attempted to generate model or scaling laws which would widen the applicability of their experiments or analyses.

Model Analysis

This purpose of this model analysis is to design scaled experiments that will ensure that models will adequately simulate the blast pressure histories of detonation of full-scale or prototype explosive containers. The model analysis is general and allows for confinement of the explosives. In our particular experiments, however, the explosive charge was unconfined and, therefore, the appropriate model analysis is a special subcase of this analysis derived by ignoring terms relating to confinement of the explosive.

The model analysis is performed using the Buckingham PI theorem[3-5]. The first step in such an analysis is to list the parameters entering other analysis by careful definition of the problem. The problem being considered is that of a confined explosive or propellant. It is suspended above a flat, infinitely long and infinitely wide, reflective surface. This surface is considered to be infinitely stiff, parallel to the surface of the ground and extending to infinity in all lateral directions. In this analysis, we determine the laws for scaling pressures and impulses imparted to various locations along this surface.

Numerous parameters are needed to characterize all aspects of this problem. Table 1 is a list of parameters characterizing properties of the explosive charge, the containment structure, the air gap between the charge and the reflecting surface, and the response which is the load imparted to

Table 1. List of parameters

Symbol	Parameter	Fundamental Dimensions	Properties Being Characterized
E	energy in explosive	FL	charge
r	characteristic dimension of explosive	L	charge
r_i	shape factor for explosive	-	charge
γ_e	explosive products specific heat ratio	-	charge
ρ_e	explosive density	FT^2/L^4	charge
a_e	explosive detonation velocity	L/T	charge
δ	effective limits for explosive detonation	L	charge
ℓ	characteristic dimension of container	L	container
ℓ_i	shape factor for container	-	container
σ_u	ultimate stress of container	F/L^2	container
ρ_c	container density	FT^2/L^4	container
P_a	ambient air pressure	F/L^2	air
a_a	sonic velocity in air	L/T	air
γ_a	specific heat ration in air	-	air
R	standoff distance	L	geometry of encounter
θ	angle between radius vector for Rand horizon	-	geometry of encounter
P	applied pressure	F/L^2	response
I	specific impulse	FT/L^2	response
t	time	T	response

the target as a function of time. By applying conventional methods of dimensional analysis [4,5] one generates the representative non-dimensional ratios of pi terms given in Table 2 and finally the model law given in Table 3. The replica model law satisfies all the non-dimensional ratios and was used as the basis for the experiments.

Table 3 is essentially Sach's model law for scaling blast loads. Additional parameters have been included in this analysis because, at small standoff distances, a more complete representation of the charge geometry including the details of charge confinement and charge size are extremely important. Since the prototype does not include confinement, the model will exclude parameters such as ultimate stress σ_u, density ρ_c, and lengths ℓ and ℓ_i which relate to a containment structure. Also, the charge does not consist of pellets of explosive and the only requirement on δ is that the charge is above the critical diameter below which it will not detonate properly. Scaling air blast using replica or Sach's modeling law has long been accepted procedure and references 6 and 7 present a fairly complete discussion of scaling air blast.

If one were to write an equation for pressure, impulse or time at some position on a target, he would be defining a fourteen-dimensional space. The general solution is a fourteen-dimensional space, because the three response pi terms, 14, 15 and 16 are functions of the first thirteen pi terms. Fortunately, many of these parameters can be treated as abstract numbers, that is, some of the variables are essentially constant and thus can be cancelled from the analysis. For example, we can assume that γ_a, γ_e, a_e, a_a, ρ_e, ρ_c, σ_u, and P_a are all invariant. If the experiment does not involve pellet or flake explosive and the experiment is scaled above the critical charge dimension δ, this term can also be ignored. Since the charge is not confined in the prototype, pi terms 4 and 5 can be excluded. Under these circumstances, pi terms 14, 15 or 16 are functions of pi terms 1, 2, 6, 9, 10, 11 and 13. In functional format, this could be written (after dividing pi terms 14 and 15 by pi term 13) as equation (1) for pressure, equation (2) for impulse and equation (3) for duration.

Table 2. List of Pi terms

π_1	R/r	geometric similarity
π_2	r_i	
π_3	δ/r	
π_4	ℓ/r	
π_5	ℓ_i	
π_6	θ	
π_7	γ_a	similar atmospheres
π_8	a_e/a_a	kinematic similarity (similar velocities)
π_9	$\frac{\rho_e a_a^2 r^3}{E}$	modified Sach's scaling
π_{10}	$\frac{\rho_c a_a^2 r^3}{E}$	
π_{11}	$\frac{\sigma_u r^3}{E}$	constitutive similarity
π_{12}	γ_e	similar explosives
π_{13}	$\frac{P_a r^3}{E}$	Sach's scaled pressure; scaled responses
π_{14}	$\frac{P r^3}{E}$	
π_{15}	$\frac{I a_a r^2}{E}$	scaled impulse; scaled responses
π_{16}	$\frac{a_a t}{r}$	scaled time; scaled responses

Table 3. Replica modelling law

Symbol	Parameter	Scale Factor
$r, R, r_i, \delta, \ell, \ell_i$	lengths	λ
θ *	angle	1.0
γ_a, γ_e	ratios of specific heats	1.0
a_e, a_a	velocities	1.0
ρ_e, ρ_c	densities	1.0
σ_u	container strength	1.0
E	energy release	λ^3
P_a, P	pressure	1.0
I	specific impulse	λ
t	time	λ

* For convenience in presenting the data in graphical form, the angle θ will be represented by its horizontal (x) and vertical components (R).

$$P = f_1 \left(\frac{R}{r}, r_i, \theta, \frac{r^3}{E}\right) \tag{1}$$

$$\frac{I}{r} = f_2 \left(\frac{R}{r}, r_i, \theta, \frac{r^3}{E}\right) \tag{2}$$

$$\frac{t}{r} = f_3 \left(\frac{R}{r}, r_i, \theta, \frac{r^3}{E}\right) \tag{3}$$

Since similar explosives are being used, the above equations can be written in a more familiar form by substituting the mass W (usually in kg or lb_m) of the charge for its energy E and rearranging pi terms. Thus, one can rewrite the above equations in the functional format which follows:

$$P = f_1 \left(\frac{R}{r}, r_i, \theta, \frac{R}{W^{1/3}}\right) \tag{4}$$

$$\frac{I}{W^{1/3}} = f_2 \left(\frac{R}{r}, r_i, \theta, \frac{R}{W^{1/3}}\right) \tag{5}$$

$$\frac{t}{W^{1/3}} = f_3 \left(\frac{R}{r}, r_i, \theta, \frac{R}{W^{1/3}}\right) \tag{6}$$

The equations shown above in functional format were used to design our test apparatus so that we would properly model the prototype situation; that is, a charge detonating close to a reflecting surface such as a wall. The design engineer needs to be able to determine what the loading on this wall will be in order to make it survive an explosion. Since only the pressure and impulse are required to determine the loading to the wall, only equations (4) and (5) need to be considered. Both of these equations describe a five parameter space. To properly model the experiment, one must replicate the pi terms shown as independent variables in the equations. These are the ratio of standoff distance to characteristic dimension of the charge (R/r), the charge shape factor (r_i), the scaled location (θ or x/R),

and the scaled distance $(R/W^{1/3})$. The *ratio* (r_1) requires that one use the same charge geometries in prototype and experiment. The ratios (R/r) and $(R/W^{1/3})$ require that similar geometries be used for the placement of the charge with respect to the measurement location. Finally, the similar scaled location (θ) specifies that the orientation of the charge relative to the measurement point be the same in prototype and experiment. That is, for a given charge orientation with respect to a reflecting surface (a wall in the prototype), measurements in the prototype and model are comparable at equal angles from the axis of symmetry. The model law also states that when the above four pi terms are satisfied, the model and prototype will produce similar pressures at similar scaled distances $(R/W^{1/3})$ and that impulse for the model and prototype will scale as $1/W^{1/3}$ at similar scaled distances $(R/W^{1/3})$. Different charge geometries violate the ratio (R/r) and are not strictly comparable. However, for the charge geometries considered in this experimental effort, which were spheres, cubes and cylinders, we will present the data on the same graphs, but different curves.

EXPERIMENTAL PROGRAM

General

To accomplish the objectives of this experimental program, techniques for measuring peak reflected pressures and specific impulses at close standoff distances from high explosives had to be devised and evaluated. The close standoff distances chosen for this program ranged from 0.12 to $1.2 m/kg^{1/3}$ ($0.3 - 3.0\ ft/lb_m^{1/3}$) where distance is measured from the center of the charge to the top of the measurement platform. To save time and money for the government, it was decided to use small charges and one experimental setup. To examine the validity of the model law, the test program was devised in such a manner that different scale size charges at equivalent scaled distances were detonated. The test charges were also chosen in such a manner that, for a given scaled distance from the nearest measurement point (that is, directly below the charge), measurements would be taken over a relatively large range of lateral positions or angles along the horizon. However, because only one size reflected surface was used, the smaller scale experiments had a wider range of lateral measurement locations.

As mentioned previously, the test program consisted of exploding Pentolite spheres, and cubes and cylinders (length-to-diameter ratio of 1.68) of Composition C-4 explosive. The experimental program which we conducted consisted of 75 tests as shown in Table 4. As shown in the table, there were thirteen shots involving nominal 0.454 kg (1.0 lb) Pentolite spheres at various scaled distances. The Pentolite spheres were used to test our measurement techniques and compare with previous investigators[8-14]. They were carefully cast and thus had homogeneous densities and their spherical geometry offered a higher degree of symmetry than that of the cubes and cylinders of Composition C-4 explosive charges. This made the measurements less sensitive to the manner in which the charges were suspended above our measurement platform. The repeatability of the measurements taken from the explosion of the Pentolite spheres as shown in a later section of this paper demonstrates the homogeneity of the charge, its proper positioning above the measurement platform, and the accuracy of our measurement apparatus.

Table 4. Experimental program

Geometry	Charge Weight (lb_m)	Scaled Distance ($ft/lb_m^{1/3}$)	Number of Tests
Sphere	1.0	3.0	2
		1.5	2
		1.3	1
		0.6	4
		0.3	4
Cube	0.125	1.0	3
		0.6	2
		0.3	2
	0.25	3.0	3
		1.5	3
		0.6	4
		0.3	3
	1.5	3.0	3
		1.5	3
		0.6	3
		0.3*	3
Cylinder	0.125	1.0	3
		0.6	2
		0.3	2
	0.25	3.0	3
		1.5	3
		0.6	3
		0.3	3
	1.5	3.0	3
		1.5	3
		0.6	3
		0.3*	3

$1\ lb_m = 0.454\ kg$

$1\ ft/lb_m^{1/3} = 0.40\ m/kg^{1/3}$

* Four of these tests were conducted at scaled distances of 0.45 (i.e., two cylinders and two cubes) in order to prevent extensive test apparatus damage.

Also shown in Table 4 are the charge weights, scaled distances and number of shots fired for the cubes and cylinders of Composition C-4 explosive. It should be noted that four of the tests, two 0.68 kg (1.5 lb_m) cubes, and two 0.680 kg (1.5 lb_m) cylinders, were not conducted at a scaled distance of 0.12 $m/kg^{1/3}$ (0.3 $ft/lb_m^{1/3}$), as originally planned, but rather at a scaled distance of 0.18 $m/kg^{1/3}$ (0.45 $ft/lb_m^{1/3}$). This was done to prevent extensive damage to the test apparatus as had occurred for the cube, and to a lesser degree for the cylinder, placed at a scaled distance of 0.12 $m/kg^{1/3}$ (0.3 $ft/lb_m^{1/3}$) above the surface of the test platform.

Measurement Platform and Gage Positions

In order to perform the measurements, a reflective surface was designed which would withstand the blast loads from charges detonated at close standoff distances. This reflective surface consisted of a steel plate bolted to four sturdy steel legs which were bolted to anchors placed in a reinforced concrete pad. The test table top varied from 57 mm to 64 mm (2 1/4 to 2 1/2 inches) in thickness and had lateral dimensions of 0.91 m by 0.91 m (36 in. x 36 in.) as shown in Figure 1. The center, or thinnest, portion of the table was designed to accommodate a removable 6.4 mm (1/4 in.) thick insert plate which could be replaced after being damaged from the blast pressures and impulses. Also, insert plates with different hole sizes could be used to allow for insertion of different gages with different diameters or different combinations of pressure gages and impulse plugs.

During a test, the charge was suspended by a light string from a crossbar which was high above the table so as not to interfere with the blast measurements. The charges were secured laterally by joining light string to the charge and the four corners of the test table. All charges were positioned above the center of table, which was also where a pressure transducer or impulse plug was positioned, and standoff distance was measured from the center of the charge to the center of the top of the table. Cubical charges were positioned with one face parallel to the surface of the table and corners oriented in the same

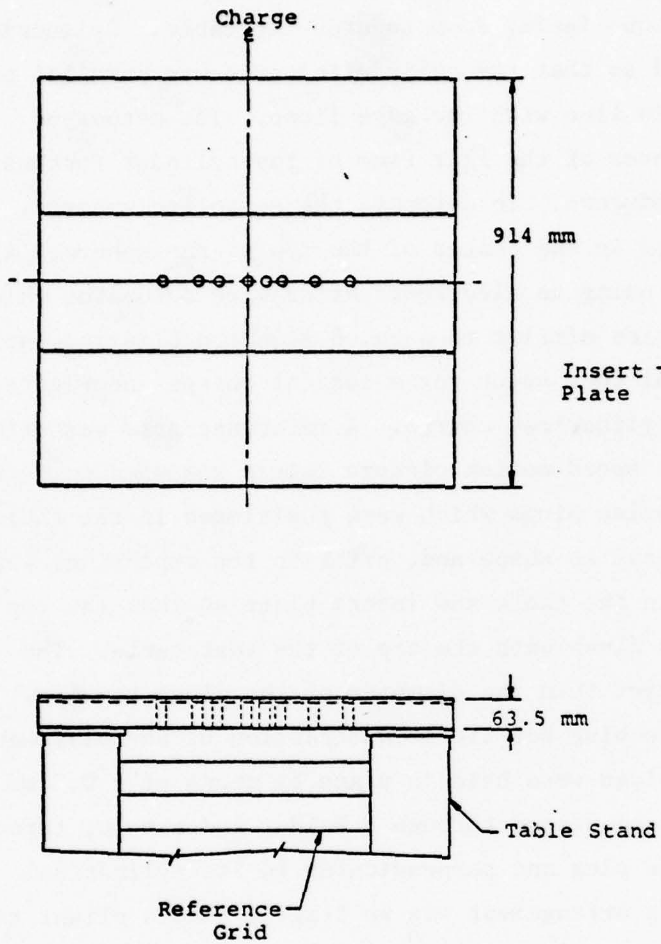


Figure 1. Experimental Reflecting Table

position as the table corners. The detonator was placed in the center of the top face of the cube facing down towards the table. Cylindrical charges were positioned so that the cylindrical axis was parallel to the table surface and in line with the gage lines. The detonator was inserted in the center of the flat face of the cylinder furthest from the pressure transducers. To detonate the Pentolite spheres, the detonator was placed in the center of the top of the sphere. All charges were detonated using an electronic bridgewire detonator which has output characteristics similar to a No. 8 standard blasting cap. Figure 2 shows a typical test setup for a cubical charge and Figure 3 shows the setup for a cylindrical charge. A reference grid was attached to the table and a high speed motion picture camera was used to determine the velocity of the impulse plugs which were positioned in the table. The plugs were cylindrical in shape and, prior to the explosion, were placed through a hole in the table and insert plate so that the top surface of the plug was flush with the top of the test table. The holes were slightly larger than the diameter of the plugs to allow for free movement of the plug but little diffraction of the blastwave around the plug. The plugs were held in place by means of a 0.5 mm thick piece of pencil lead placed through a holder and a hole, through the bottom-center of the plug and perpendicular to its cylindrical axis. This plug holding arrangement was so fragile that a slight tap on the top of the plug would allow it to fall. The camera-grid arrangement was used to determine the velocity of the plugs after the explosion. The mass of the plug, its cross-sectional area, and its velocity were used to determine reflected specific impulse at the plug location.

Test Procedure

All experiments conducted in this program were fired at an outdoor explosives laboratory on SwRI grounds. A typical test was conducted by first installing the pressure and impulse measurement systems on the reflecting table top. Most of the tests used four to six pressure transducers and up to three impulse plugs. On fourteen of the tests, only impulse plugs were used with no pressure transducers. The trans-

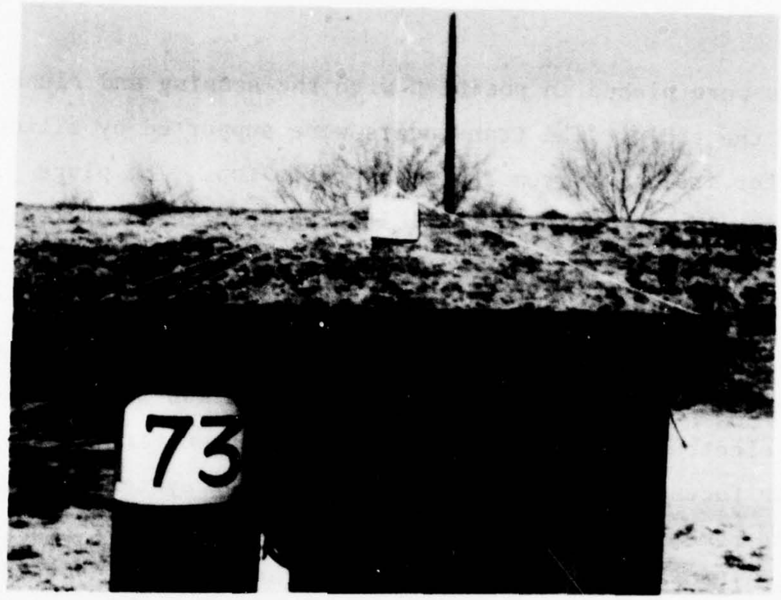


Figure 2. Typical Setup - Cube

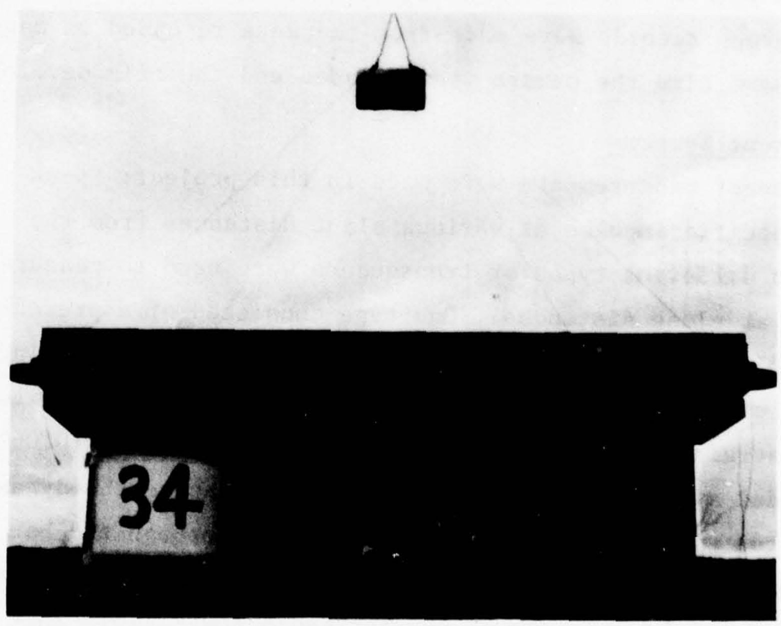


Figure 3. Typical Setup - Cylinder

ducers and plugs were placed in position with the sensing end flush with the top of the table. The transducers were supported by silicon rubber inserts for isolation from the steel table top. The plugs were supported in place with thin pencil lead which offered negligible resistance to plug motion when loaded by the blastwave.

Once in position the pressure transducer was connected to a junction-box adjacent to the concrete path supporting the test table. Continuity from transducer back to the recording van was then checked and the record electronics properly setup. At the same time the high-speed camera was focused and loaded, and the lighting system properly positioned. The remote firing circuit was then checked before the charge was suspended at the correct standoff from the table top, supported to keep it in place, and finally connected to the firing circuit. After a short countdown,the power was switched on the camera which in turn remotely triggered the exploding bridgewire firing system.

Polaroid prints were obtained from the oscilloscopes and display unit. Oscillograph records were made from the data recorded on magnetic tape. At the same time the camera was unloaded and the film developed.

Measurement Systems

Two types of measurements were made in this project: peak pressure and specific impulse at various slant distances from the explosive. Two different types of transducers were used to measure the peak pressures at close distances. One type consisted of a pressure bar made of 6.35 mm (0.25 in.) diameter high strength steel having a yield strength of about 2,100 MPa (300,000 psi). A pair of longitudinally-oriented strain gages, with a sensing length of 1.57 mm (0.062 in.), were epoxy bonded at opposite sides of the bar to measure the dynamic strain associated with the stress pulse propagated through the bar from the high-explosive detonations. These transducers have an upper pressure limit equal to the yield strength of the bar and a lower limit that depends on the sensitivity of the strain gages and record instrumentation. For practical purposes their range for measuring peak pressures is approximately 35 - 2,100 MPa (5,000 - 300,000 psi). The rise time of

the bar transducers is about 0.25 μs. However, in several of the measurements the angle of obliquity between the blastwave and the table top was such that the limiting factor on transient response was the time required by the blastwave to travel over the end of the bar. The output of the pressure bars were connected to a Wheatstone bridge. The signal was then passed through a signal conditioner and recorded on a dual-beam oscilloscope.

The second type of transducers used to make the pressure measurements in this program were of the piezoelectric type. These transducers utilize a ceramic or crystal to obtain an electrical charge which is proportional to the stress imparted by the blast wave. Depending on the peak pressure expected on a given test, different models were used. Two models, ST-4 and ST-2 made by Susquehanna Instruments and one model, 102A03, made by PCB Piezotronics were used in this project. The output of the piezoelectric transducers was recorded on an Ampex FR-1900 Widebank II magnetic tape recorder.

Because the two types of transducers for measuring the peak pressures are physically quite different, they were calibrated using different apparatus. The pressure bars were calibrated both dynamically and statically. Prior to calibration, their sensitivity was computed using the strain gage and bridge parameters. Dynamic calibration was accomplished with a Hopkinson split pressure bar system.

A static calibration was also performed on the pressure bars. In this case, all 24 bars made for this program were calibrated by fixing the end nearer the strain gages and applying two different known loads at the free end. Each bar was placed such that the sensing axis of the gages were on a vertical plane. In this case, the gages were connected electronically so that bending strains of opposite polarity added. The two loads produced computed stresses at the gage location of 172 MPa (25,000 psi) and 345 MPa (50,000 psi). The output of the strain gage bridge was measured with a digital voltmeter and an average sensitivity of 24,000 kPa/mv (3591 psi/mv) computed for all 24 bars. Maximum deviation of any one bar was less than 3%.

This static sensitivity is also only about 1.5% different than the dynamic value. Thus excellent agreement was found between the two.

The piezoelectric pressure transducers were dynamically calibrated using a hydraulic calibrator consisting of a triangular chamber filled with oil. Two symmetric ports are provided for flush mounting a reference and a test transducer. The pressure pulse is generated by dropping a weight down a guide tube onto a piston which extends through the top of the chamber. This device produces a half-sine, positive pressure pulse with peak amplitudes from 0.7 MPa (100 psi) to more than 100 MPa (14,500 psi) and rise times of 1 to 2 milliseconds. Different weights and drop heights are used to vary the peak amplitudes. The reference piezoresistive transducer used was first calibrated using a dead-weight hydraulic tester to check its sensitivity. It in turn was used to determine the pressure input to the test transducer. As a final pressure calibration check, a pressure bar and an ST-4 piezoelectric transducer were tested, after each was calibrated, by positioning a Pentolite explosive sphere midway between them at a standoff distance to produce a pressure level within the range of the ST-4. The peak pressures recorded were within 2% of each other, well within their calibration tolerances.

Two techniques were used for obtaining the specific impulse data in this experimental program. One of them consisted of using cylindrical plugs in holes in the rigid table top and measuring the velocity imparted by the blast wave with a high-speed motion picture camera. The impulse is then computed by multiplying the measured velocity, corrected for gravitational effects, by the mass of the plug and dividing by the exposed area of the plug end. This technique is very good for reflected specific impulse measurements where plug velocities are the greatest and much higher than the gravitational velocity. However, for lateral plug locations away from the normal position, the plugs see smaller impulses and are loaded by a sweeping rather than a normal blast wave so that tumbling is more pronounced. At lateral locations greater than the normal distance between the charge

and the table top, particularly for the smaller charges, the plugs produce lower than expected velocities and much more scatter in the data because of binding between the plug and the table as the plug begins to tumble, and velocities which barely exceed gravitational effects so that the resolution of this measurement technique is inadequate to provide a valid velocity measurement.

The second technique for obtaining specific impulse was to integrate the positive phase of good pressure-time histories recorded from the pressure transducers. Most of these were obtained from the piezoelectric pressure transducers although the pressure bars did produce useable records primarily at the normal location for those cases in which the strain gage installations remained intact for the full duration of the loading. In either case, considerable judgement is required to select pressure traces which will yield valid impulse data. Any extraneous signals recorded along with pressure data or drift by the transducer produces amplified errors in the impulse data so that considerable scatter and invalid impulse data result if the pressure-time histories to be integrated are not selected judiciously.

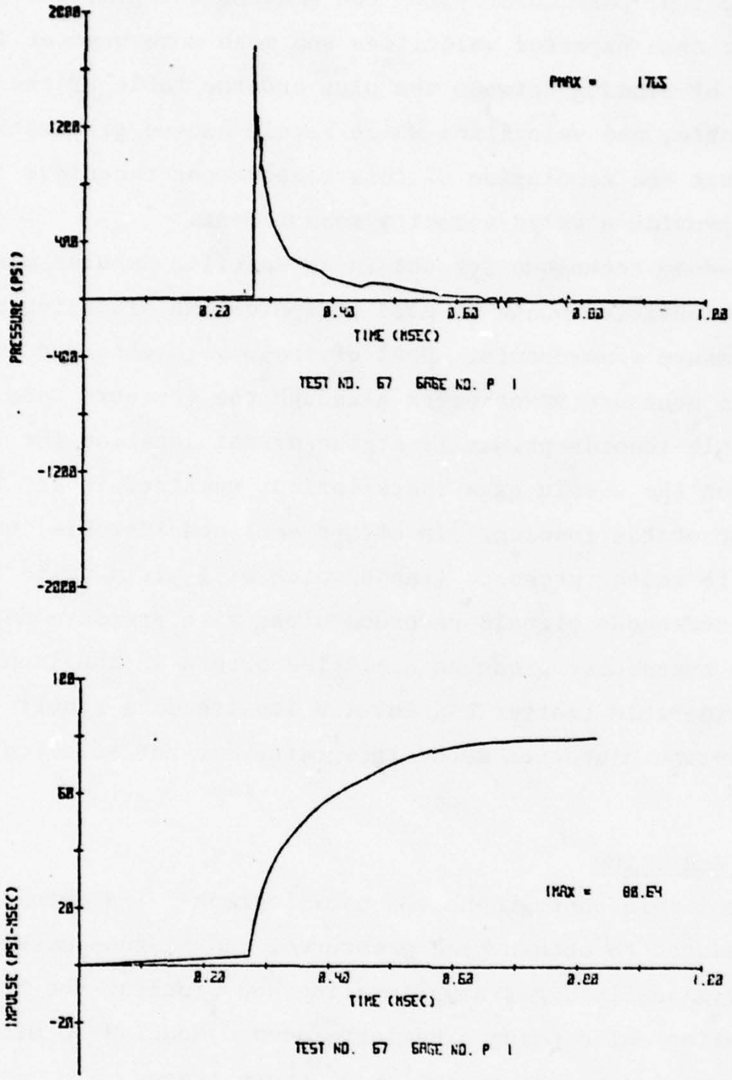
Data Reduction

The polaroid photographs and oscillograph rolls obtained on each test were reduced to obtain peak pressures, and in some cases impulses, by manually digitizing, scaling and plotting the traces with engineering units using a Hewlett-Packard Model 9830 microprocessor system. Figure 4 shows some samples of these traces.

Data reduction to determine impulse, I, from the plugs was to measure their velocity, V, from the high speed camera using a Vanguard Motion Analyzer. Then the reflected impulse is given by the impulse-momentum theorum for plugs of known mass, M, and frontal area, A.

$$I = \frac{MV}{A} \tag{7}$$

The average velocity due to gravity was calculated and subtracted from the actual plug.



1 psi = 6.895 kPa

Figure 4. Sample of Processed Data for Test No. 67, x/R = 0

RESULTS AND DISCUSSION

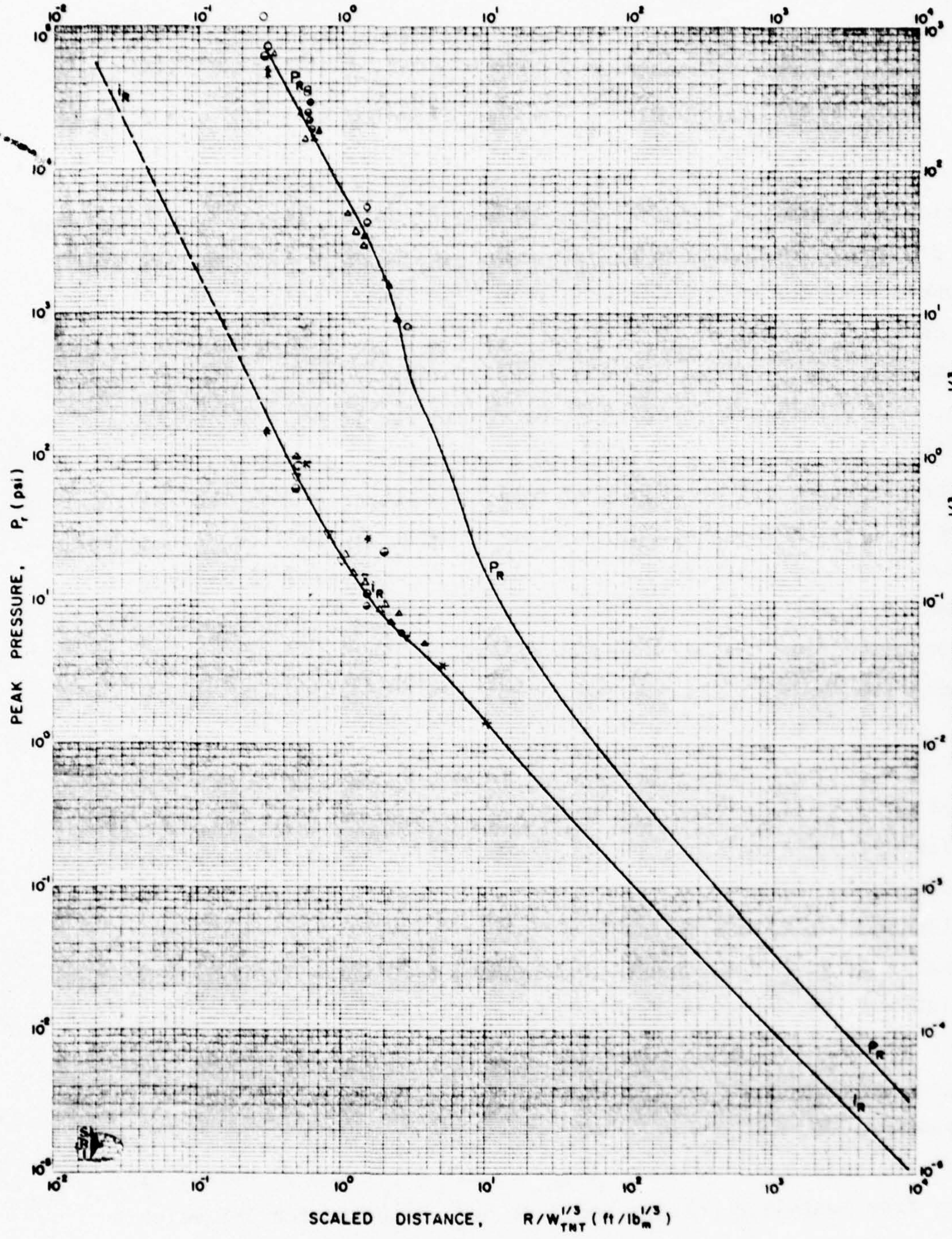
General

The results of this experimental effort are presented in this section in graphical form. The scaling law derived in the model analysis and presented in Equations 4-6 states that pressures and impulses are a function of the scaled distance ($R/W^{1/3}$), scaled location (θ or x/R), the charge shape factor (r_i), and the ratio of standoff distance to characteristic dimension of the charge (R/r). In the general case then, a five parameter space must be considered to properly scale the results. For the case of reflected measurements, x/R equals 0, the number of parameters decreases to four. To properly describe the relationships of these two cases, considerable testing is required, particularly if more than one scale is used. However, for the geometries used in these tests, the ratio (R/r) is relatively constant so that its effect is considered negligible to reduce the number of variables in the scaling law.

To insure and provide confidence that any measuring technique were valid, a series of tests was conducted using a 0.454 kg (1 lb) Pentolite spheres at various standoff distances and compared with the results published by other investigators[7-14]. Figure 5 contains comparable TNT curves for peak reflected pressure and specific impulse developed by W. E. Baker and published in reference 1. These curves are based on much more recent experimental data than are the curves in TM5-1300[8]. The dashed region of the reflected specific impulse i_r in Figure 5 is an analytic fit, but has very good physical justification. References 1 through 14 contain the data on which the curves in Figure 5 are based.

The points contained on Figure 5 are experimental values from blasts from Pentolite spheres and have been adjusted for TNT weights by comparing the relative energy of the explosive and TNT as given in reference 15.

In Figure 5 note the general agreement in the data accumulated by the various researchers.



○ Pentolite Spheres, SwRI (ref. 14)
● Pentolite and C-4 Spheres, SwRI (ref. 11)
△ Pentolite Spheres, BRL M-1499 (ref. 10)
▲ Pentolite Spheres, BRL M-1347 (ref. 13)
▽ Pentolite Spheres, BRL M-1182 (ref. 12)
* TM5-1300 (ref. 8)

Figure 5. Normally Reflected Shock Wave Parameters for Spherical TNT Explosions in Free Air

The asterisks plotted in Figure 5 are values from the curves in TM5-1300 and do not always lie on the empirical curve. The curves in TM5-1300 were actually developed from a theoretical/semi-empirical analysis performed by Sune Granström[16] and have little empirical validation. A comparison of the data plotted in Figure 5 reveals that the data, both reflected pressure and reflected specific impulse, generated by SwRI compare well with the data generated by the Ballistic Research Laboratories and other investigators. Reflected pressure values from TM5-1300 agree with the data from SwRI[14] and other investigators for scaled distances ($R/W_{TNT}^{1/3}$) greater than 0.2 m/kg$^{1/3}$ (0.5 ft/lb$^{1/3}$) but less than the data from SwRI and other investigators for scaled distances less than 0.2 m/kg$^{1/3}$ (0.5 ft/lb$^{1/3}$). For scaled distances greater than 4 m/kg$^{1/3}$ (10 ft/lb$^{1/3}$), reflected specific impulse values from TM5-1300 agree with the data generated by SwRI and other investigators, but are higher for scaled distances greater than 0.16 m/kg$^{1/3}$ (0.4 ft/lb$^{1/3}$) and less than 4 m/kg$^{1/3}$ (10 ft/lb$^{1/3}$), and are lower for scaled distances less than 0.16 m/kg$^{1/3}$ (0.4 ft/lb$^{1/3}$).

Pressure Data

Figure 6 through 12 present all the pressure data recorded in this project. Note that the axes of the graphs presented in Figure 5 through 12 are labeled in bolometric and English units. Figure 6 is a plot of the normally reflected pressure as a function of the scaled distance. Except for the sphere tests which used only one charge size, three different charge sizes (scales) were used. Since the different charge sizes were scaled as dictated by the replica model law, the pressure data for each different geometry becomes strictly a function of the scaled distance, and the different geometries form a family of curves which show the relationship created by the charge shape factor. In Figure 6 one can observe that the repeatability of the control Pentolite sphere tests is excellent but for the other two geometries is not as good. This indicates that the scatter for the cube and cylinder tests is most probably the result of the difficulty in exactly positioning these charges over the test table, and nonuniformities and lack of homogeniety in the hand-molded Composition C-4 charges. For the cubes and cylinders, correct placement and alignment becomes more critical than for the spheres because even a slight gust

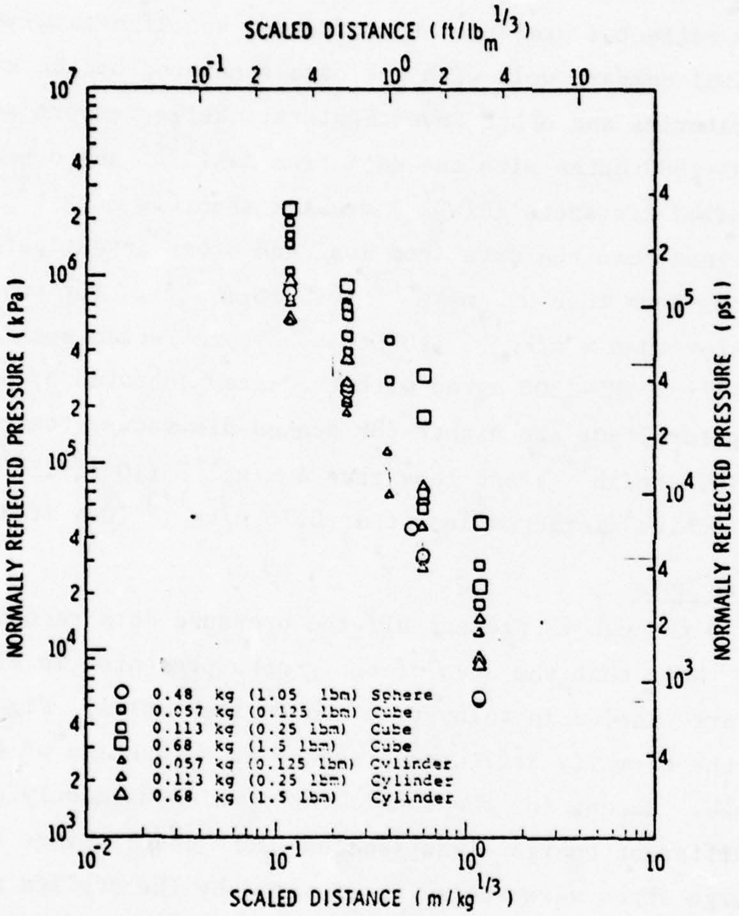


Figure 6. Reflected Peak Pressures vs. Scaled Distance for Spheres, Cubes and Cylinders

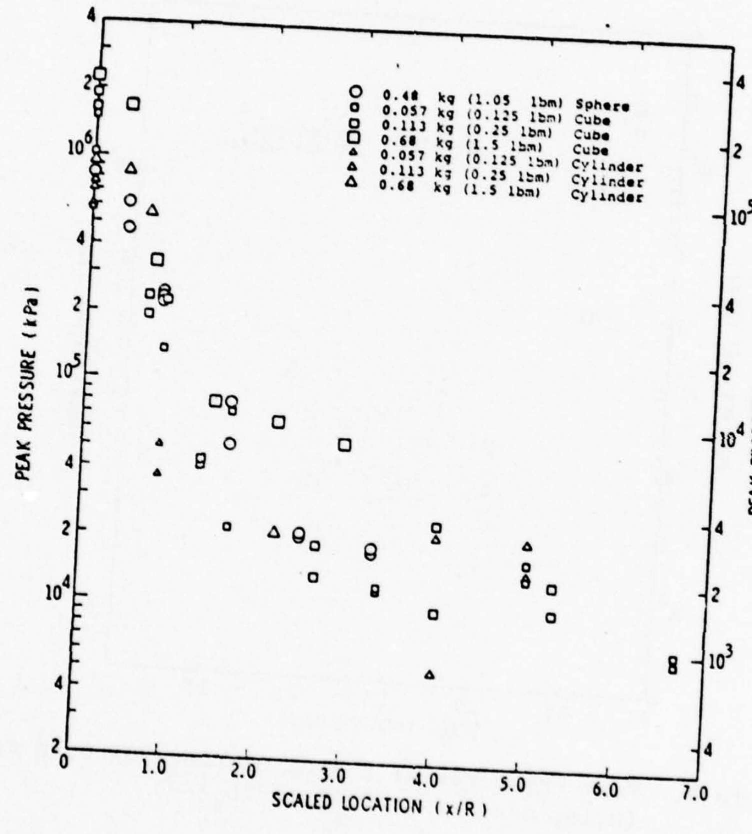


Figure 7. Peak Pressures at Scaled Distance of 0.12 $m/kg^{1/3}$ (0.12 $m/kg^{1/3}$ = 0.3 $ft/lb_m^{1/3}$)

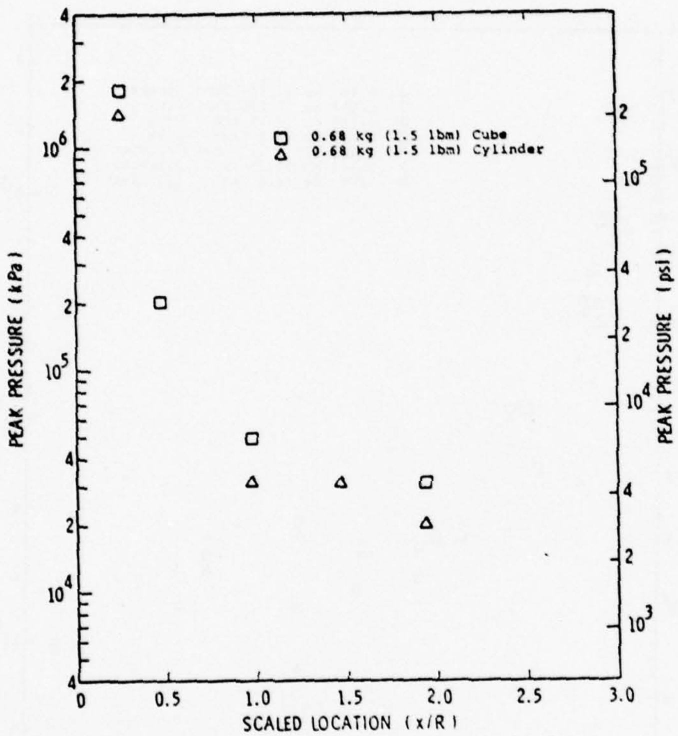


Figure 8. Peak Pressures at Scaled Distance of 0.18 m/kg$^{1/3}$ (0.18, m/kg $^{1/3}$ = 0.45 ft/lb$_m$$^{1/3}$)
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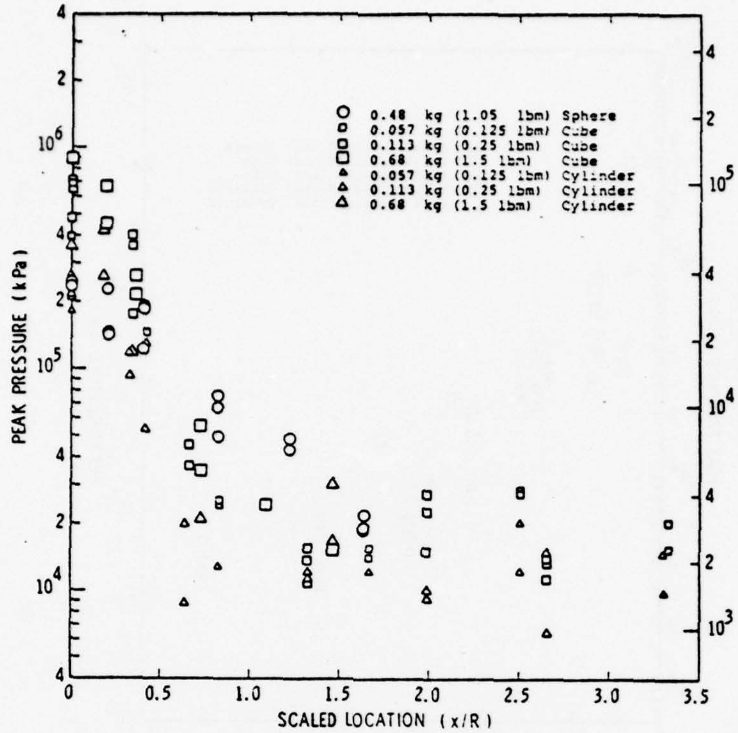

Figure 9. Peak Pressures at Scaled Distance of 0.24 m/kg$^{1/3}$ (0.24 m/kg$^{1/3}$ = 0.60 ft/lb$_m^{1/3}$)

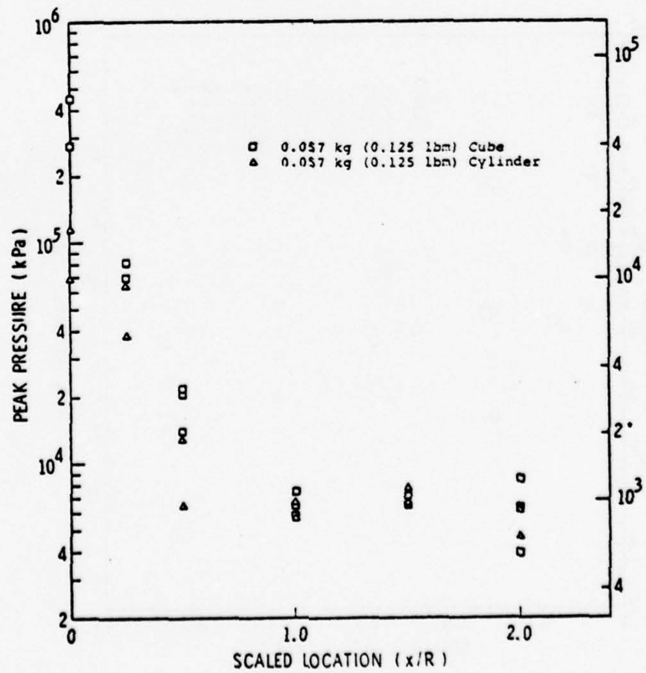

Figure 10. Peak Pressures at Scaled Distance of 0.4 m/kg$^{1/3}$ (0.4 m/kg$^{1/3}$ = 1.0 ft/lb$_m^{1/3}$)

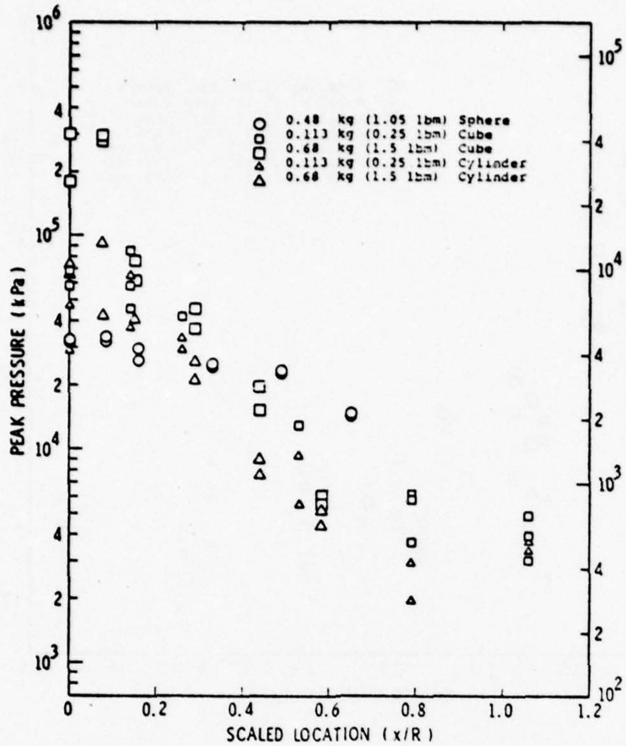

Figure 11. Peak Pressures at Scaled Distance of 0.6 $m/kg^{1/3}$ (0.6 $m/kg^{1/3}$ - 1.5 $ft/lb_m^{1/3}$)

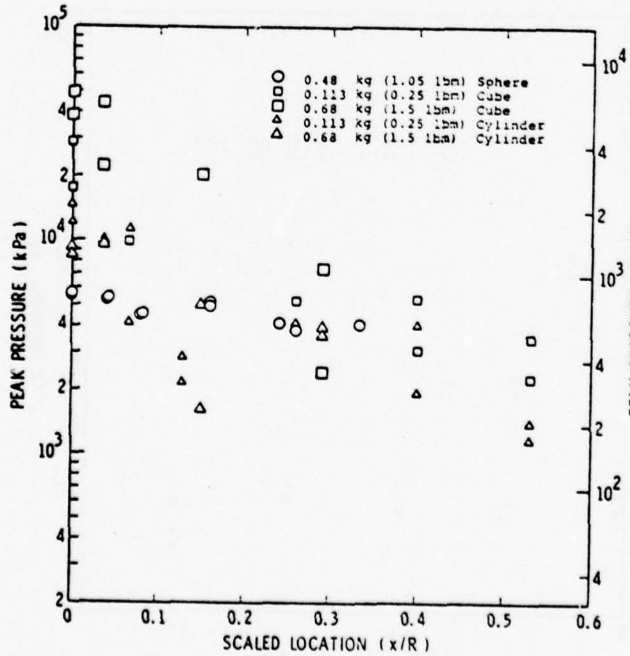

Figure 12. Peak Pressures at Scaled Distance of 1.2 $m/kg^{1/3}$ (1.2 $m/kg^{1/3}$ = 3.0 $ft/lb_m^{1/3}$)

pressures are about the same regardless of geometry. As was the case with the reflected pressures, the data scatter for the tests using spherical charges is very low while that for the cubic and cylindrical tests was again greater. Finally, note that in general for all scaled distances and charge geometries used, the peak pressures decrease very rapidly as x/R increases from 0 to 1.0. For values of x/R greater than 1.0, the decrease in pressure becomes much more gradual.

Impulse Data

The specific impulse data are presented in similar fashion as the peak pressure data both in metric and English units. Figure 13 shows the normally reflected specific impulse as a function of scaled distance. As was the case with the peak pressure data, more scatter is present on the cube and cylinder tests than on the sphere tests. Within each type of explosive, scaling is again shown, even with these limited data. Specific impulse for the cubic charges deliver higher impulses than the other two geometries. Figures 14 through 19 show the scaled specific impulse as a function of scaled location at a given scaled distance. A similar relationship as was seen with the pressure data is shown by the impulse data. For small values of x/R the cubes generate much higher impulses than the cylinders and spheres, but as x/R increases the impulses of the three geometries coalesce. In general, the sphere tests produce more repeatable results.

Note that these figures represent data from the two techniques used for obtaining impulse. The unfilled symbols are the data from the impulse plugs while the slashed symbols are the integrated impulses from the pressure traces. The plug data extend only to values of x/R of about 1.0, particularly for the smaller charges used, because for greater values of scaled distance, the plug technique as used in this program does not provide valid data. On the other hand, integrated impulse data was obtained for most values of x/R within the physical limits of the reflecting table used. In general, the data from these two measurement systems agree well at scaled distances where both techniques yielded data points. For others, the different sets of data fall in line with each other for the different charge geometries.

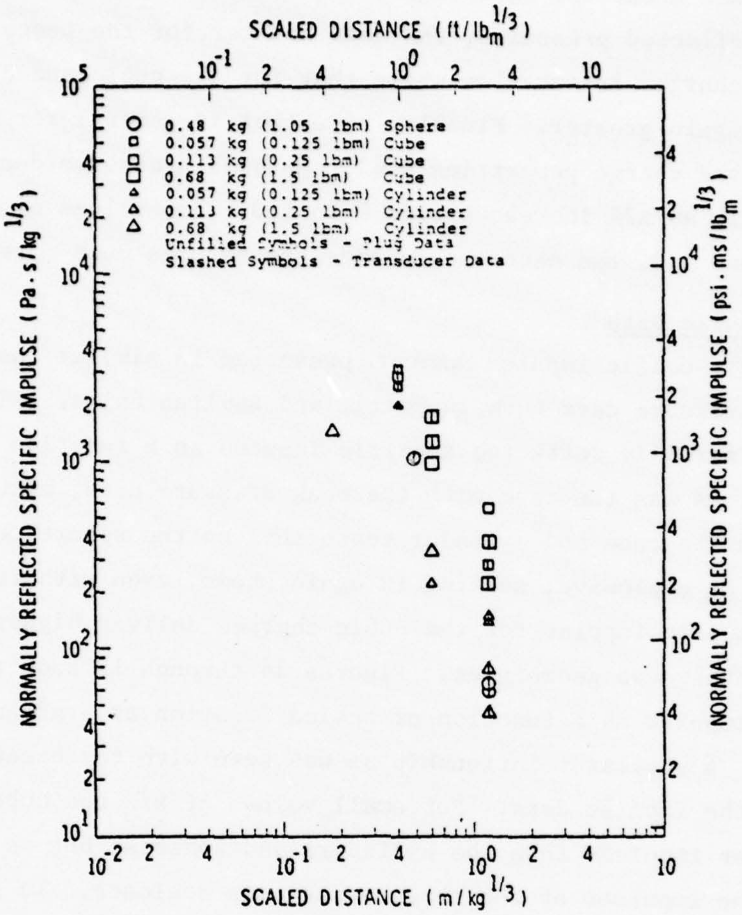

Figure 13. Reflected Specific Impulse vs. Scaled Distance for Spheres, Cubes and Cylinders

of wind during the test or a slight tilt in positioning would induce a significant different in the reflected pressure measured. This was verified in this testing program by one test using a cubic charge in which the cube was tilted 45° along the vertical plane intersecting the transducer locations on the table. A peak reflected pressure of about ten times smaller was recorded for this experiment conducted using a 0.68 kg (1.5 lb_m) cube of C-4 at a scaled distance of 0.24 $m/kg^{1/3}$ (0.6 $ft/lb_m^{1/3}$). Another factor which contributed to the scatter of the cube and cylinder data is that composition C-4 explosive, though easily molded, is not as uniform as cast Pentolite.

However, even with the scatter present one can see that, in general, scaling is verified within each geometry which used up to three different charge sizes. Some exceptions can be noted for this statement, in particular, the cube data at a scaled distance of 0.6 $m/kg^{1/3}$ (1.5 $ft/lb_m^{1/3}$). This discrepancy is most likely due to the probability of not getting high-order detonation for these small charges and the fact that charge placement errors are more significant in the smaller scale experiments.

The charge shape is definitely a significant factor in the reflected peak pressure generated by the different geometries. The cubic charges, for the range of scaled distances used, produce much higher peak reflected pressures than the other two geometries. The cylinder data falls in between, though only slightly higher than that for the spherical charges.

For peak pressures other than reflected, the scaling law contains one additional parameters, the scaled location (x/R). For each geometry, then, the pressure data are a function of this scaled location at each scaled distance. These data are shown in Figures 7 through 12. Note that on these figures, the pressures at x/R = 0 are the reflected pressures shown in Figure 6. For small values of x/R the charge shape factor is an important parameter, especially at the closer scaled distances, exemplified by the higher pressures the cubes generate than the other two charge shapes. However, as x/R increases, the peak

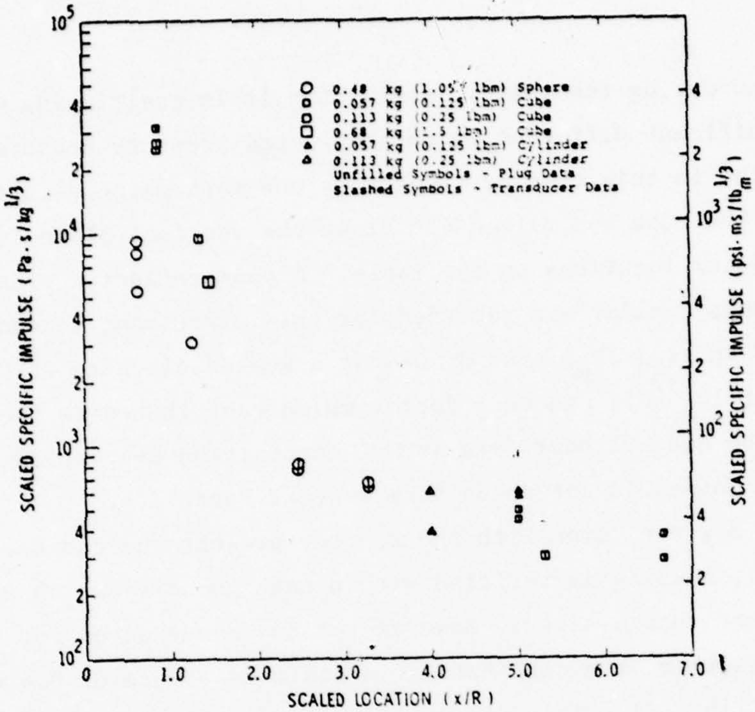

Figure 14. Scaled Impulse at Scale Distance of 0.12 m/kg$^{1/3}$
(0.12 m/kg$^{1/3}$ = 0.3 ft/lb$_m$$^{1/3}$)

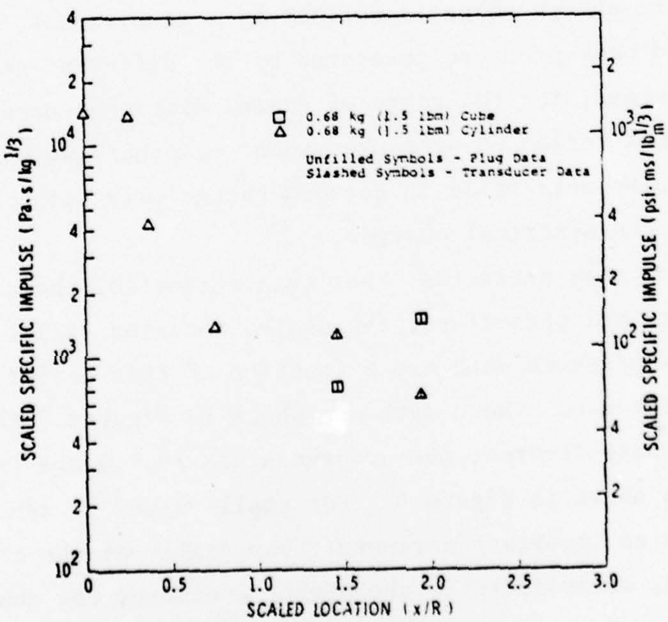

Figure 15. Scaled Impulse at Scale Distance of 0.18 m/kg$^{1/3}$
(1.18 m/kg$^{1/3}$ = 0.45 ft/lb$_m$$^{1/3}$)

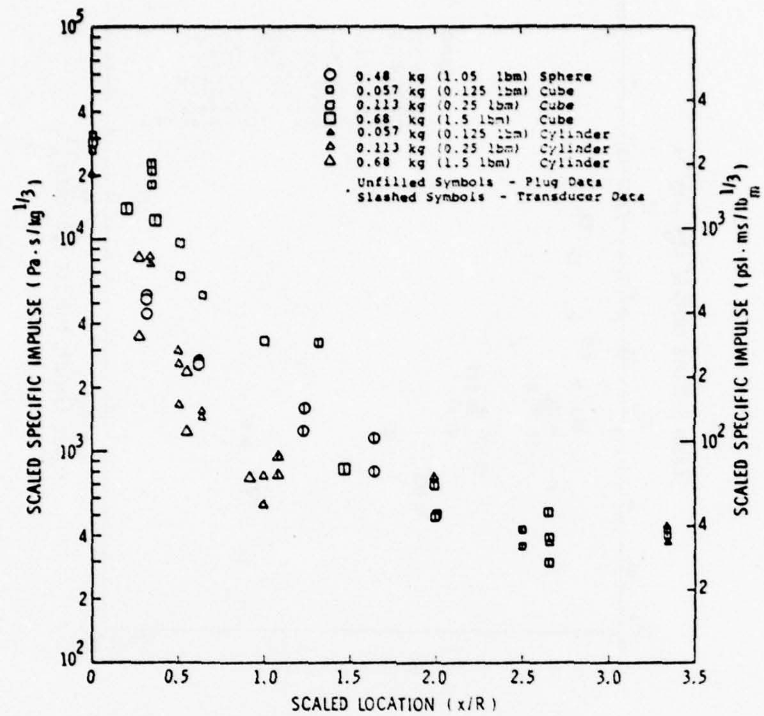

Figure 16. Scaled Impulse at Scale Distance of 0.24 m/kg$^{1/3}$ (0.24 m/kg$^{1/3}$ = 0.60 ft/lb$_m^{1/3}$)

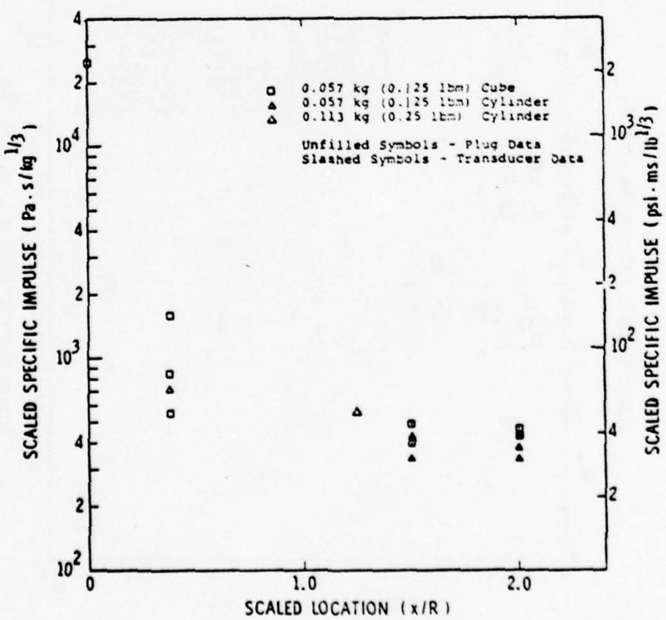

Figure 17. Scaled Impulse at Scale Distance of 0.4 m/kg$^{1/3}$ (0.4 m/kg$^{1/3}$ = 1.0 ft/lb$_m^{1/3}$)

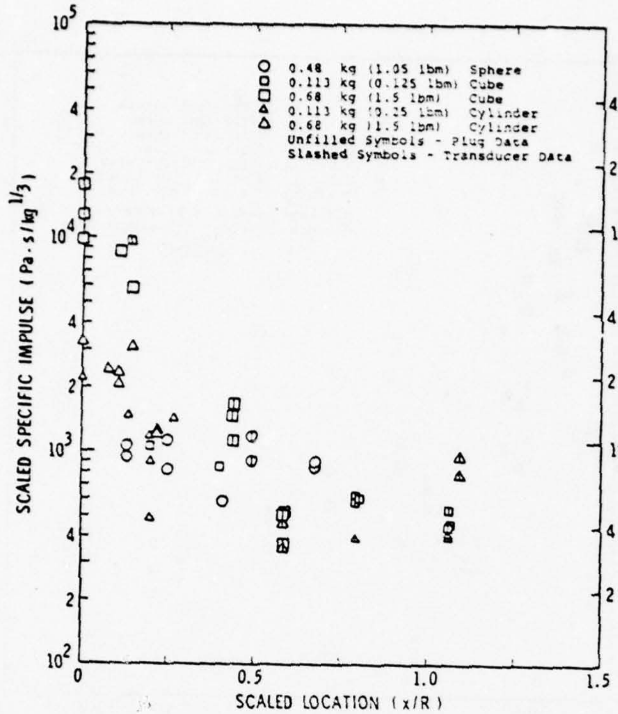

Figure 18. Scaled Impulse at Scale Distance of 0.6 m/kg$^{1/3}$
($0.6 \text{ m/kg}^{1/3} = 1.5 \text{ ft/lb}_m{}^{1/3}$)

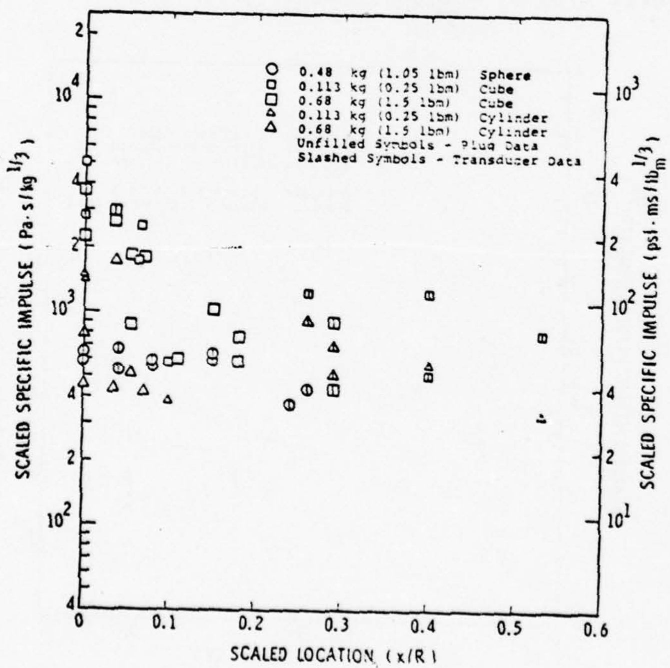

Figure 19. Scaled Impulse at Scale Distance of 1.2 m/kg$^{1/3}$
($1.2 \text{ m/kg}^{1/3} = 3.0 \text{ ft/lb}_m{}^{1/3}$)

SUMMARY AND CONCLUSIONS

The principal conclusions and observations reached as a result of the tests conducted on this program are:

(1) The validity of the scaling law was verified by using several charge sizes and the reflected pressure and impulse measurements obtained are directly applicable to similar prototype configurations.

(2) Pressures and impulses produced by the sphere tests had considerably less scatter than the cube and cylinder tests.

(3) For the range of scaled distances tested, reflected pressure and impulse for the cubes is about 2 to 3 times higher than the spheres. The cylinders produce about the same levels as the spheres.

(4) The cubic geometry yields higher, and the cylinders slightly higher pressures and impulses than the spheres at small lateral distances ($x/R < 1.0$) from the normal location. But as the lateral distance increases ($x/R > 1.0$) all three geometries produce approximately the same levels of pressure and impulse.

(5) Although both pressure and impulse were measured with different types of transducers or measurement techniques, good agreement was found in all the data.

(6) The pressure bar technique accurately measures peak reflected pressures from 34.5 to 2,070 MPa (5,000 to (300,000 psi). Piezoelectric transducers used in this program accurately portray pressure and specific impulses for pressures ranging from about .069 to 138 MPa (100 psi to 20,000 psi). Impulse plugs can be used most accurately when their initial velocity due to the blast wave is several times greater than

gravitational effects over the distances over which the plugs travel through the explosive products before becoming visible to the camera, and when they are used at off-axis angles of less than about 45° ($x/R = 1.00$).

ACKNOWLEDGEMENTS

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REFLECTED BLAST MEASUREMENTS AROUND MULTIPLE DETONATING CHARGES*

by

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ABSTRACT

This paper presents the results of an experimental program in which blast parameters were measured at close standoff distances from three simultaneously detonated charges. The charges were arranged in three different geometrical configurations: grouped, horizontal and vertical arrays. A series of single charge tests was also conducted to establish a baseline from which the effects of multiple charges could be determined. The parameters measured included peak pressure, specific impulse, positive duration and time of arrival. The results presented in this paper concentrate on the pressure and impulse measurements.

The major conclusion was that blast parameters from grouped array charges are less than those for equivalent single charges, and that regions of enhanced pressure and impulse exist for horizontal and vertical arrays relative to single charges.

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INTRODUCTION

This paper describes an experimental program conducted by Southwest Research Institute (SwRI) in support of the Army Plant Modernization Program.[(1)*] In a plant process there are often multiple explosive sources within a single room, on a conveyor or near a barricade. Currently, structures which may be loaded by simultaneous or near simultaneous multiple detonations are designed according to Section 4-17 of Reference 2. According to this document, the impulse loading on the structure is approximated by the numerical sum of the impulse which would be generated by each individual explosion whenever the combined duration is less than 1/3 of the response time of the structure. For combined durations longer than 1/3 the structure response time, the actual pressure-time history should be replaced by a fictitious peaked triangular pulse similar to that for a single explosion. The objective of this program was to investigate blast phenomena near a reflective surface due to multiple simultaneous detonations at small scaled distances. This information will be used to supplement the information contained in Reference 2. Eventually, it is hoped that this information will lead to a more realistic design of buildings used for the manufacture of explosives and propellants.

The blast parameters of several charge geometries were measured at different charge spacings and standoff distances. At large distances, the shock fronts from several charges detonated simultaneously should coalesce and be more or less indistinguishable from that of a single charge with an equivalent amount of explosive. To ensure that measurements were made before the individual shock fronts had begun to coalesce, the transducers were placed at small scaled standoff distances ($Z \leq 1.2$ m/kg$^{1/3}$ or 3.0 ft/lb$^{1/3}$). Since this was an exploratory program, the tests were organized in the following manner.

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*Superscript numbers denote references included at the end of the paper.

- The number of charges was held constant at three.
- All three charges were detonated simultaneously.
- The in-process explosive sources were simulated with Composition B spheres.
- Three charge geometries were investigated: Grouped, Horizontal and Vertical Arrays.
- The spacing between charges in the horizontal and vertical array tests was uniform.

The blast parameters measured included peak pressure, specific impulse, positive duration and time of arrival. The pressure-time traces were recorded with piezoelectric transducers and the impulse was obtained by integrating the pressure histories. The results presented in this paper concentrate on the pressure and impulse measurements.

EXPERIMENTAL PROGRAM

General

The objective of this test program was to investigate the blast effects on a barricade due to the simultaneous detonation of three charges at small scaled distances. To accomplish this objective, a technique for measuring the blast pressures and impulses at scaled distances of 0.32 to 1.2 $m/kg^{1/3}$ (0.80 - 3.0 $ft/lb^{1/3}$) was devised. In order to perform the measurements, a reflective surface, capable of withstanding the loads due to the exploding charges and of holding the transducers in place, had to be designed. After some consideration, it was decided to use the ground as the reflecting plane rather than a more conventional test stand because in some tests the charges would be separated by as much as 2.08 m (6.8 ft.). Accurate reflected blast measurements require a reflective surface which is very stiff

and effectively infinite in extent in the plane being loaded. This would require a longer, wider and thicker steel test stand than was practical, therefore the ground was chosen as the most advantageous reflecting plane.

Test Arrangement

In the experiments, nine transducers were installed in separate canisters and buried in a straight line in the ground. The canisters, see Figure 1, were placed so that the surface plate and the transducer diaphragm were flush mounted with the ground surface. The canisters were spaced at equal intervals of 0.36 m (1.2 ft.). Either one or three spherical Composition B charges were suspended above the line of transducers so that a line drawn through the center of the charges was parallel to the transducer line. Photographs of the test set-up for horizontal and grouped array tests are included in Figure 2.

The detonators used in this program were Reynolds Industries RP-81 electronic bridgewire (EBW) detonators. These EBW's are used extensively in applications where simultaneity of detonations of multiple charges is desired. When connected in series, up to eight charges can be detonated with a simultaneity not worse than 0.125 microseconds.

Test Program

Four series of tests were conducted as summarized in Table 1. In Test Series 1, a single charge weighing either 0.65 kg (1.43 lb) or 2.29 kg (5.05 lb) was detonated from 0.29 to 1.56 m (0.95 to 5.1 ft) above the reflecting plane. This series of tests was conducted to validate the experimental technique and transducer calibration by generating data which could be compared directly with data in the literature. In addition, this series of tests served as a baseline from which the effects of three charges detonating simultaneously could be evaluated. Test Series 1A was conducted to examine the validity of the model law by detonating a different scaled size charge

TABLE 1

TEST PROGRAM

Designation	Test Series	No. Shots	Charge Weight K_g (lb)	No. Charges	Charge Separation m (ft)	Standoff m (ft)	Scaled Standoff $m/Kg^{1/3}$ $(ft/lb^{1/3})$
C	1	3	0.65 (1.43)	1	-	0.29 (0.95)	0.335 (0.84)
A	1	3	0.65 (1.43)	1	-	0.437 (1.43)	0.504 (1.27)
B	1A	3	2.29 (5.05)	1	-	0.652 (2.14)	0.495 (1.25)
D	1	3	0.65 (1.43)	1	-	0.582 (1.91)	0.672 (1.70)
R	1	2	0.65 (1.43)	1	-	1.05 (3.43)	1.21 (3.04)
S	1A	1	2.29 (5.05)	1	-	1.56 (5.13)	1.18 (2.99)
E	2	3	0.223 (0.492)	3	0	0.29 (0.95)	0.332 (0.834)*
F	2	3	0.223 (0.492)	3	0	0.436 (1.43)	0.499 (1.26)*
G	2	3	0.223 (0.492)	3	0	0.582 (1.91)	0.665 (1.68)*
I	3	3	0.223 (0.492)	3	0.71 (2.33)	0.436 (1.43)	0.495 (1.25)*
J	3	3	0.223 (0.492)	3	0.71 (2.33)	0.582 (1.91)	0.665 (1.68)*
P	3	3	0.223 (0.492)	3	0.366 (1.2)	0.724 (2.38)	0.821 (2.07)*
N	3	4	0.223 (0.492)	3	0.71 (2.33)	0.724 (2.38)	0.821 (2.07)*
Q	3	3	0.223 (0.492)	3	1.07 (3.5)	0.724 (2.38)	0.821 (2.07)*
M	4	4	0.223 (0.492)	3	0.145 (0.475)	0.437 (1.43)	0.504 (1.27)*

*For these tests, R is measured to the center of mass of the charges and W is the total weight of Composition B explosive.

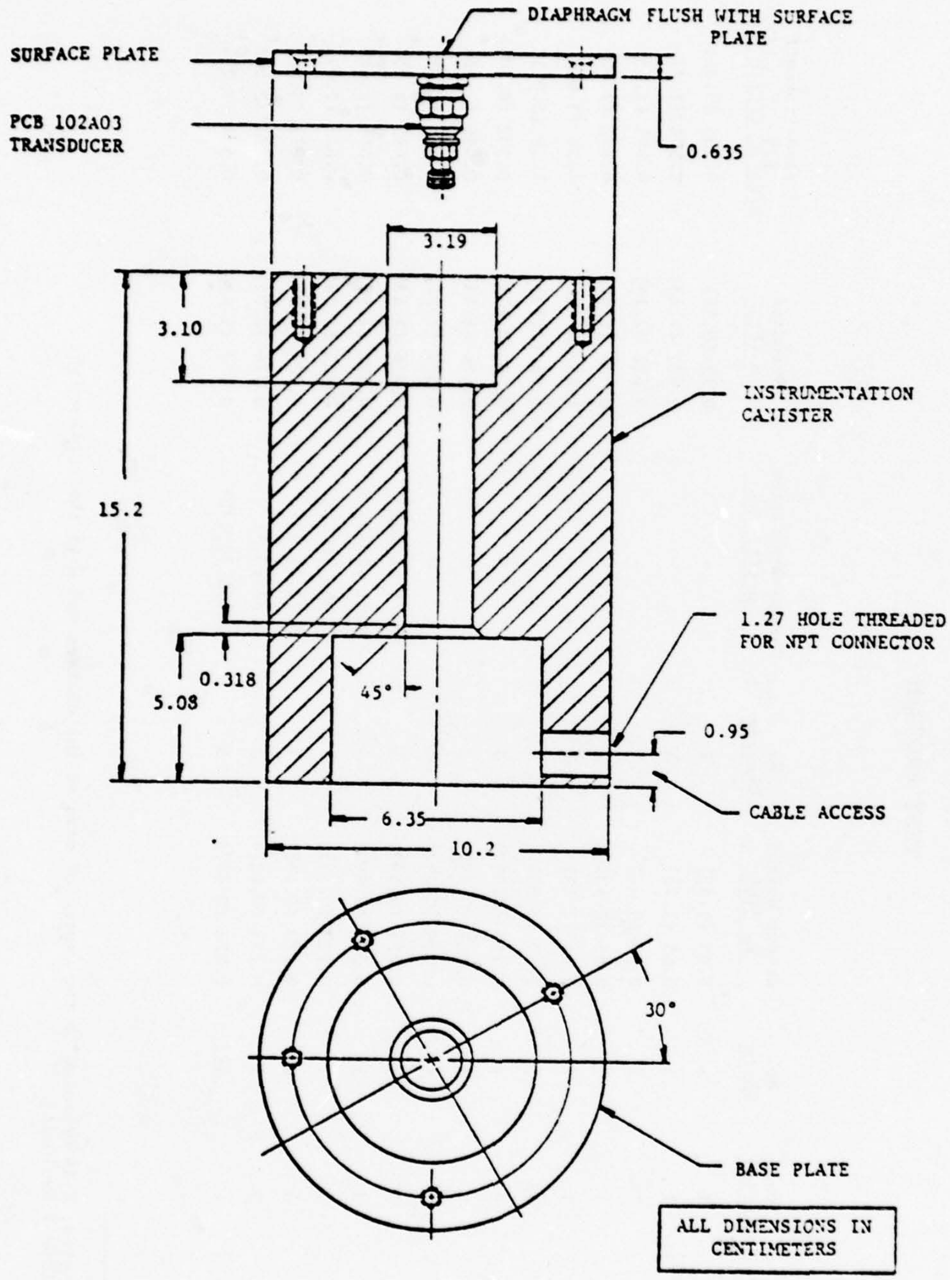

FIGURE 1. EXPLODED DIAGRAM OF THE PRESSURE MEASUREMENT ASSEMBLY

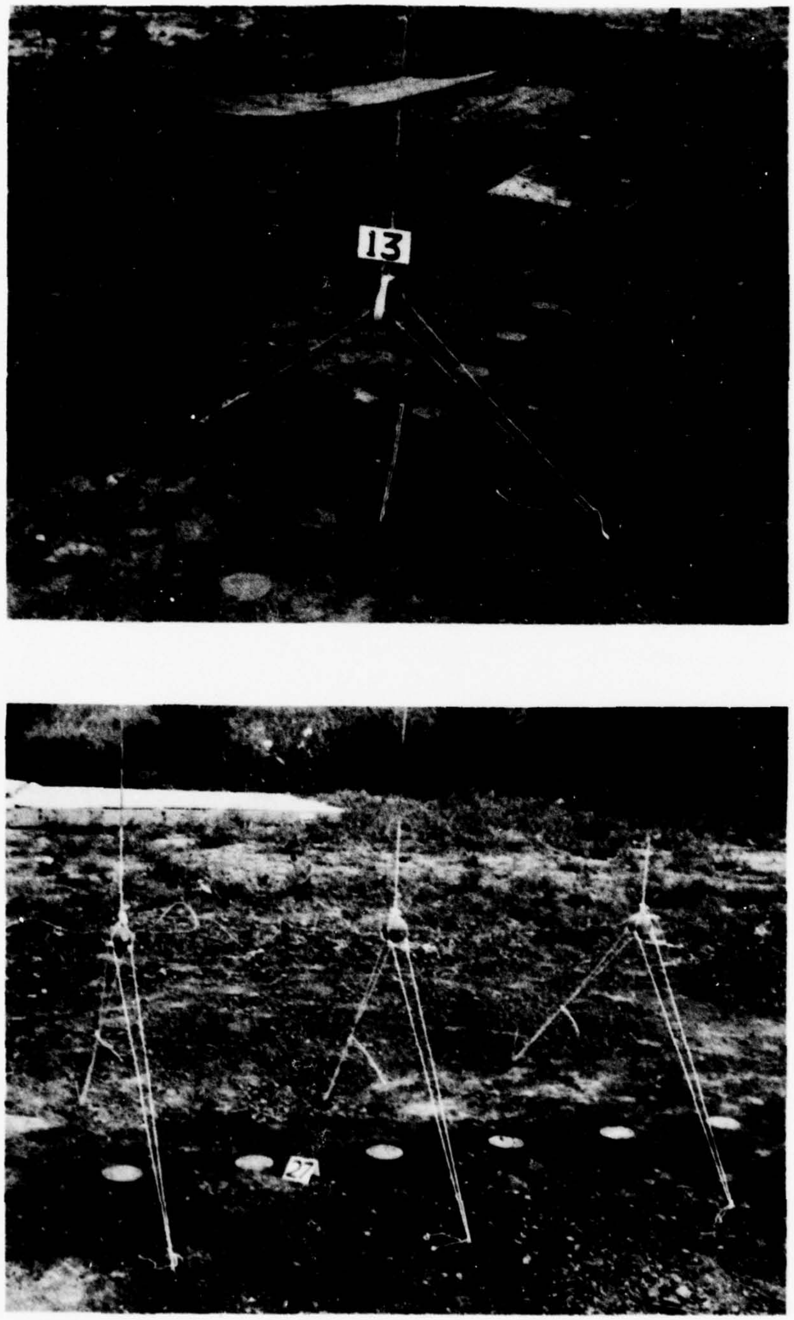

FIGURE 2. TYPICAL TEST ARRANGEMENT FOR THE GROUPED ARRAY AND THE HORIZONTAL ARRAY TESTS

at an equivalent scaled distance. A total of 15 Series 1 tests was conducted at four different scaled distances: 0.335, 0.5, 0.672, 1.2 $m/kg^{1/3}$ (0.84, 1.25, 1.70, 3.0 $ft/lb^{1/3}$). A schematic diagram of the charge placement and gage positioning is given in Figure 3a.

Test Series 2 was conducted to determine how the blast output of three charges which are grouped together, differs from the blast output of a single charge. The test configuration for this series is shown schematically in Figure 3b. Notice that the standoff distance R is measured in this case as the distance from the ground surface up to the center of mass of the three charges. A total of nine tests at the three scaled distances, Z = 0.478, 0.716 and 0.960 $m/kg^{1/3}$ (1.2, 1.81, 2.42 $ft/lb^{1/3}$), was conducted in Test Series 2. For the grouped array tests, the total weight of the three charges was used in computing the scaled distance Z. This convention facilitates comparison with the single charge test results.

Test Series 3 was conducted to investigate the variations of blast output of three charges which are distributed in a horizontal array for various charge spacings and standoff distances. The test configuration for this test series is shown schematically in Figure 3c. A total of 16 tests was conducted in this test series. Three scaled distances were investigated, Z = 0.719, 0.960 and 1.19 $m/kg^{1/3}$ (1.81, 2.42, 3.01 $ft/lb^{1/3}$), as well as three charge spacings, s = 0.366, 0.71 and 1.07 m (1.2, 2.33 and 3.5 ft). Of particular interest in this test series was the possibility of regions of enhanced pressure or impulse at gage locations between charges over what would be expected if only one charge were present.

The final test series was designed to investigate the blast output of three charges which are placed in a vertical array. This situation is shown schematically in Figure 3d. A total of four tests was conducted at a scaled distance, Z = 0.51 $m/kg^{1/3}$, (1.29 $ft/lb^{1/3}$), and a charge spacing of 0.145 m (0.475 ft). As was the case for the grouped charge

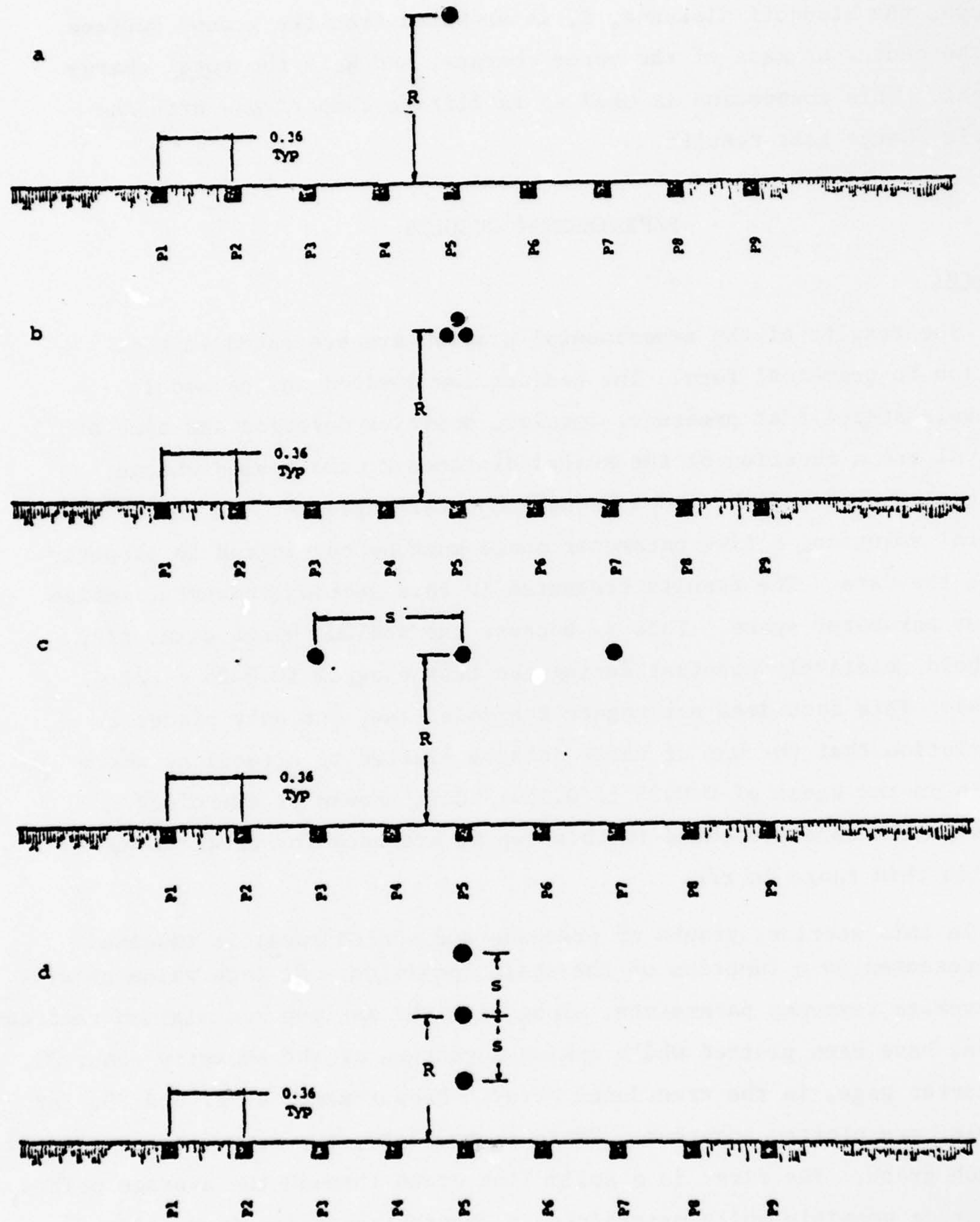

FIGURE 3. TRANSDUCER ARRANGEMENT AND CHARGE PLACEMENT FOR THE (a) SINGLE CHARGE, (b) GROUPED ARRAY, (c) HORIZONTAL ARRAY AND (d) VERTICAL ARRAY TESTS

arrays, the standoff distance, R, is measured from the ground surface to the center of mass of the three charges, and W is the total charge weight. This convention is used to facilitate comparisons with the single charge test results.

EXPERIMENTAL RESULTS

General

The results of the experimental program are presented in this section in graphical form. The scaling law derived in the model analysis states that pressure, impulse, positive duration and time of arrival are a function of the scaled distance Z, the scaled charge separation s_i/r and the shock front encounter angle Φ*. In the general solution, a five parameter space must be considered to properly scale the data. The results presented in this section, however, define a four parameter space. This is because the scaled charge size, r/R, was held relatively constant during the test program ($0.0425 < r/R < 0.154$). This fact does not negate the model law, but only places a restriction that the use of these data be limited to situations where r/R is in the range of 0.0425 to 0.154. Care should be exercised whenever the data presented in this report are used for predictions outside this range in r/R.

In this section, graphs of pressure and scaled specific impulse are presented as a function of the scaled position. At each value of x/R, the average response parameters, along with the maximum and minimum recorded values, have been plotted while taking advantage of the symmetry about P5, the center gage, in the transducer array. Measurements at P1 and P9, for example, are plotted together. Where appropriate, two curves are presented on each graph. The first is a solid line drawn through the average points as near as possible while maintaining a smooth transition from point to point and the correct slope (zero) at $x/R = 0$.

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*For convenience in presenting the data, the angle Φ will be represented on the figures and in the discussions which follow by its horizontal (x) and vertical (R) components.

The second line is transferred from the appropriate single charge figure and is presented such that the relative blast output of a single charge versus multiple charges can be visualized in a convenient manner.

For brevity, pressure and impulse measurements for only one standoff distance, $Z = 0.50\ m/kg^{1/3}$ ($1.25\ ft/lb^{1/3}$), are presented in this paper. In Reference 1, the complete collection of pressure, impulse, duration and arrival time are presented.

Pressure Data

The peak pressure data accumulated during this program are shown in Figures 4 to 7. Figure 4 summarizes the peak pressures resulting from the detonation of a single charge at a scaled distance of 0.5 $m/kg^{1/3}$ ($1.25\ ft/lb^{1/3}$) from a reflecting surface. Two scaled charge sizes were investigated in the single charge tests to validate the model analysis (0.68 kg (1.5 lb) and 2.29 kg (5.05 lb)). Since the charge size was scaled as dictated by the model law, one would expect pressure to be a function of only the position at which it was measured. This is demonstrated by the A and B series tests where a single line can be drawn through all of the test data. There is a consistent trend in the four pressure curves generated during this program. As the measuring point moves away from directly under the charge ($x/R = 0$), the peak pressure decays very slowly until x/R approaches 0.2. This narrow region of gradual pressure change is followed by a region in which the pressure decays substantially until x/R is about 1.5. For values of x/R greater than 1.5, the decay of pressure with increasing x/R is again quite gradual. These three regions may be conveniently thought of as (a) essentially reflected pressure, (b) transition from reflected to side-on pressure and (c) a region which approximates side-on pressure.

The pressure generated by three 0.23 kg (0.51 lb) charges grouped together as in Figure 3b, is shown in Figure 5. The solid curve in

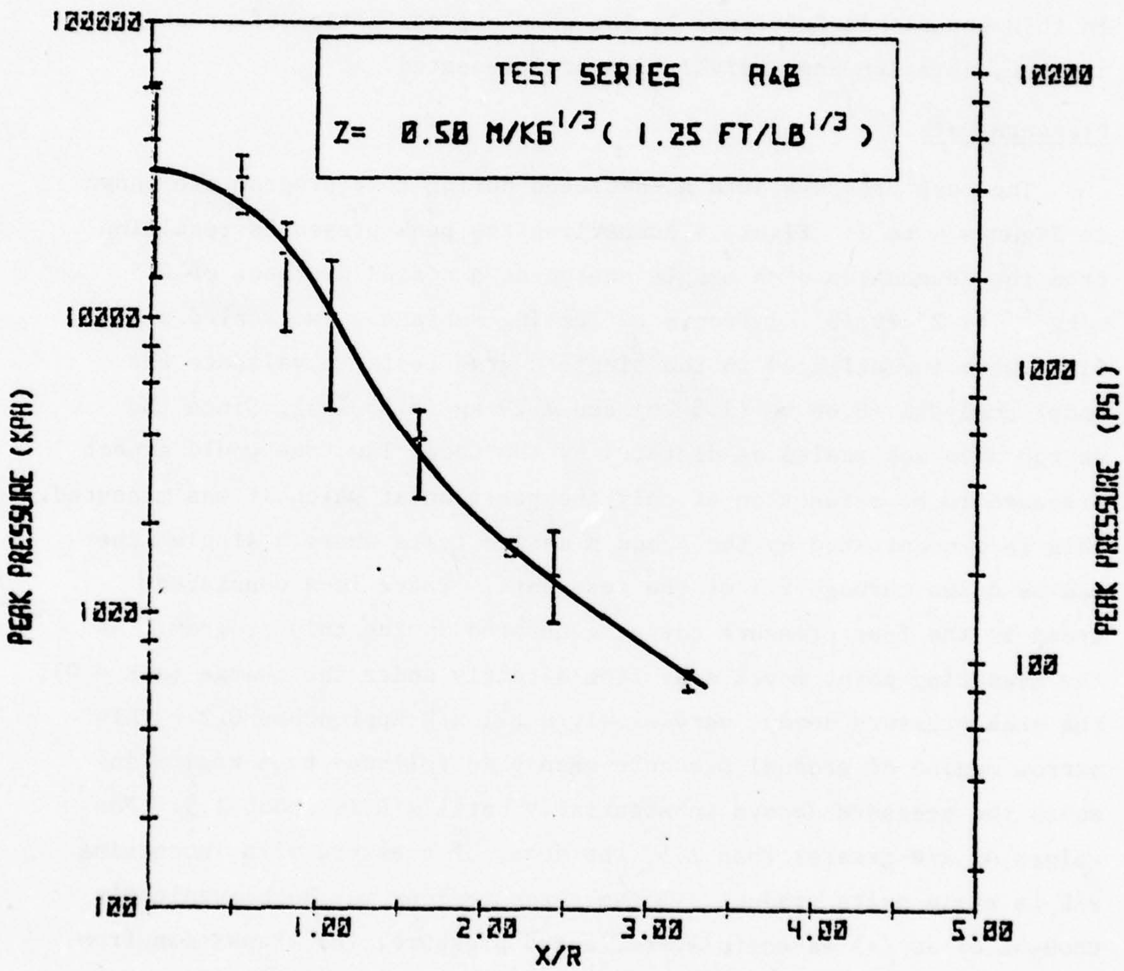

FIGURE 4. PEAK PRESSURE FOR SINGLE CHARGE TESTS SERIES A AND B.

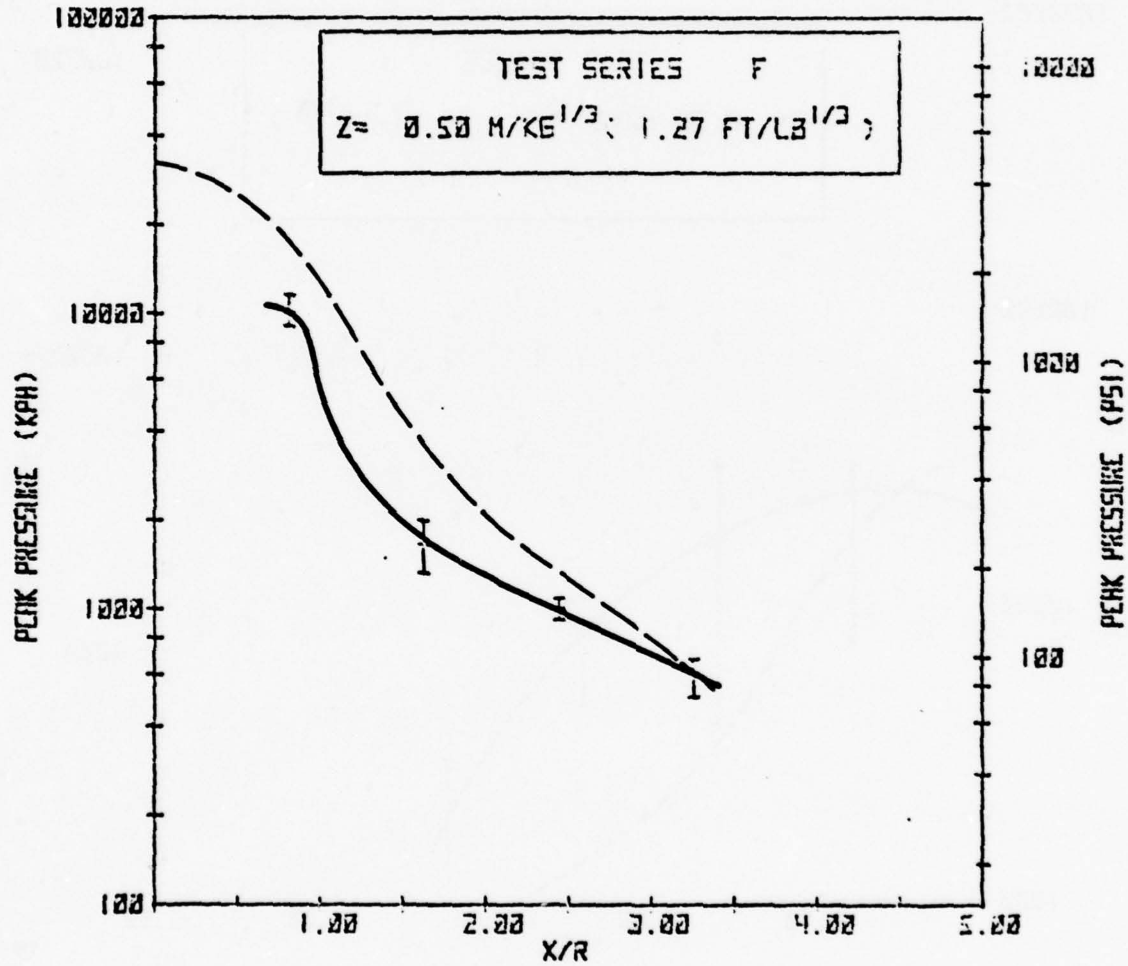

FIGURE 5. PEAK PRESSURE FOR GROUPED ARRAY TEST SERIES F.

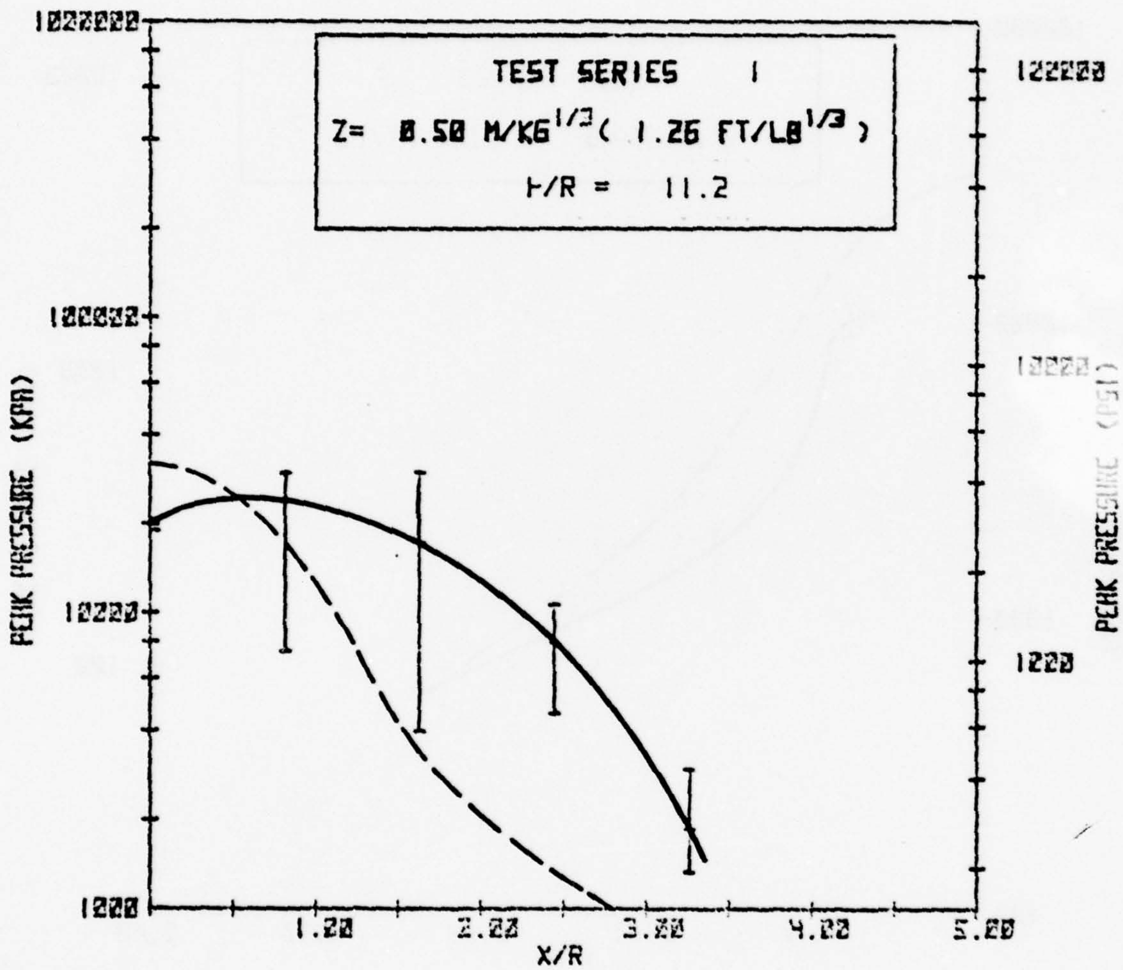

FIGURE 6. PEAK PRESSURE FOR HORIZONTAL ARRAY TEST SERIES I.

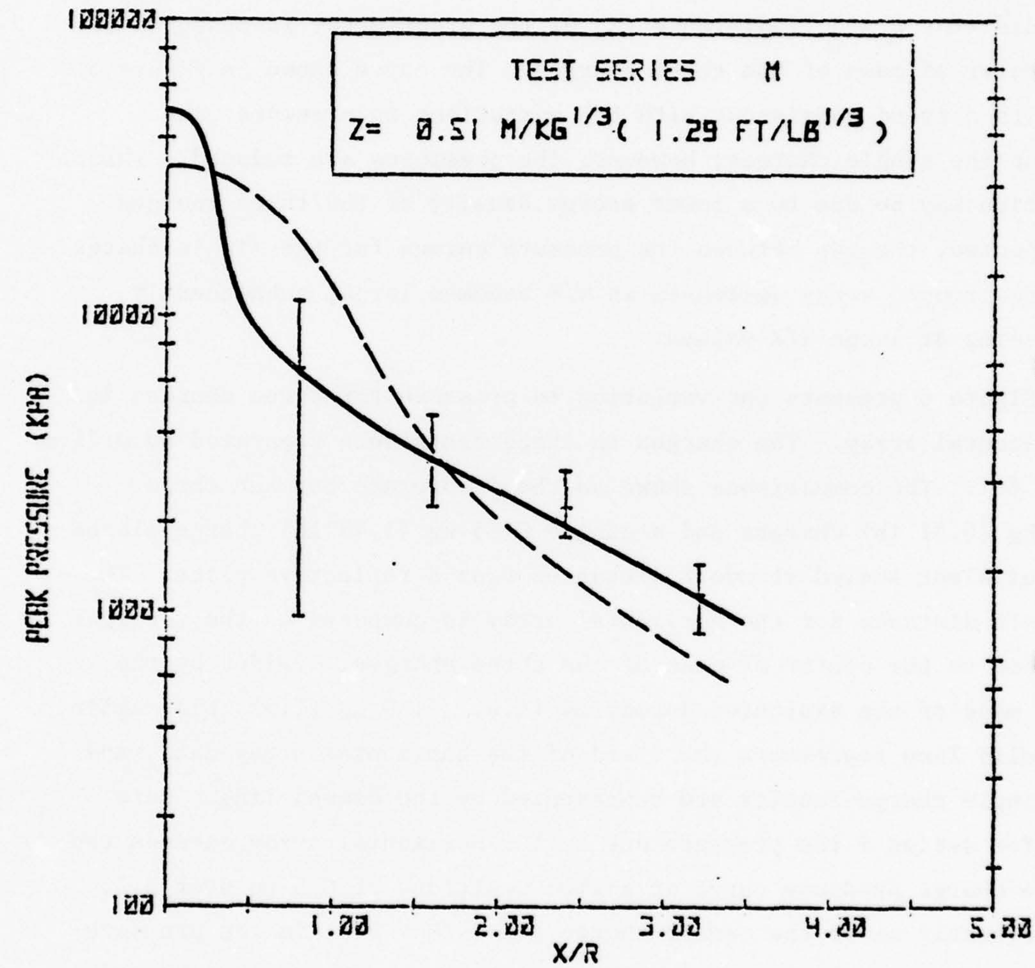

FIGURE 7. PEAK PRESSURE FOR VERTICAL ARRAY TEST SERIES M.

this figure represents an "eyeball" fit to the data generated by the grouped array. The dashed line represents the single charge data for equal scaled distances. Note that the comparison given in Figure 5 is between three 0.23 kg (0.51 lb) charges and a single 0.65 kg (1.43 lb) charge. This comparison is not intended to demonstrate agreement between single charges and grouped charges but rather to indicate differences in magnitude and tendency. The reader is reminded that standoff distance (Z) of the group array is measured to the center of mass of the three charges. The curve shown in Figure 5 exhibits a trend consistent with the variations in pressure with x/R for the single charges; however, the pressures are reduced. This reduction may be due to a lower energy density of the three charges. As expected, the gap between the pressure curves for the single charge and the grouped array decreases as x/R becomes large, subsequently coalescing at large x/R values.

Figure 6 presents the variation in pressure for three charges in a horizontal array. The charges in these tests were separated by 0.71 m (2.33 ft). The comparisons shown on the figure are between three 0.23 kg (0.51 lb) charges and a single 0.65 kg (1.43 lb) charge placed at equivalent scaled standoff distances from a reflective plane. The standoff distance for the horizontal array is computed as the vertical distance to the center of mass of the three charges, divided by the total mass of the explosive detonated (i.e., 0.69 kg (1.52 lb)). Again, the solid line represents the trend of the horizontal array data, and the single charge results are represented by the dashed line. Note that for series I the pressure due to the horizontal array exceeds the single charge pressure curve at scaled positions of 0.5 to over 3.5. Only directly under the center charge ($0 < x/R < 0.5$) is the pressure from the horizontal array less than that given by the equivalent single charge curve. This is because contributions from the outside charges arrive too late to positively reinforce the pressure measured directly under the center charge. The converse is also true; contributions

from the center charge arrive too late to contribute significantly to the pressure under the outside charges. Indeed the pressures measured directly below the charges in Figure 6 are equal within the experimental scatter. The implication of this observation is that it is unfair to compare the single charge results with the pressure from 1/3 the explosive at positions directly under the charges. However, the intention of presenting the dashed line of Figure 6 was not to demonstrate agreement between the single and multiple charge results, but rather to highlight the differences, in both magnitude and general tendency, due to distributing the charge weight in a horizontal array.

The peak pressures resulting from three charges placed in a vertical array are shown in Figure 7. In this case, the charge spacing was fairly narrow, 2.28 charge diameters. The comparison shown on Figure 7 is between three 0.23 kg (0.51 lb) charges and one 0.65 kg (1.43 lb) charge. The standoff distance for the vertical array is computed in the vertical distances to the center of mass divided by the cube root of the total mass of explosive detonated. Notice that at scaled distances approaching $x/R = 0$ and $x/R > 1.75$, the peak pressure for the vertical array tests exceeds that for a single charge. Unfortunately, only one combination of charge spacing and standoff distance was investigated for vertical arrays. It is therefore not clear whether regions of enhanced pressure would exist for different combinations of Z and s. Further vertical array tests should be conducted to see if the trends shown in Figure 7 apply to other charge spacings and standoff distances.

Impulse Data

The impulse data, obtained by numerically integrating the pressure-time curves, are given in Figures 8 to 11. All of the impulse data is plotted in scaled format $I/W^{1/3}$. As noted previously, the impulse from multiple charge tests is scaled by the total charge weight detonated. Scatter in the data, represented by the line drawn from

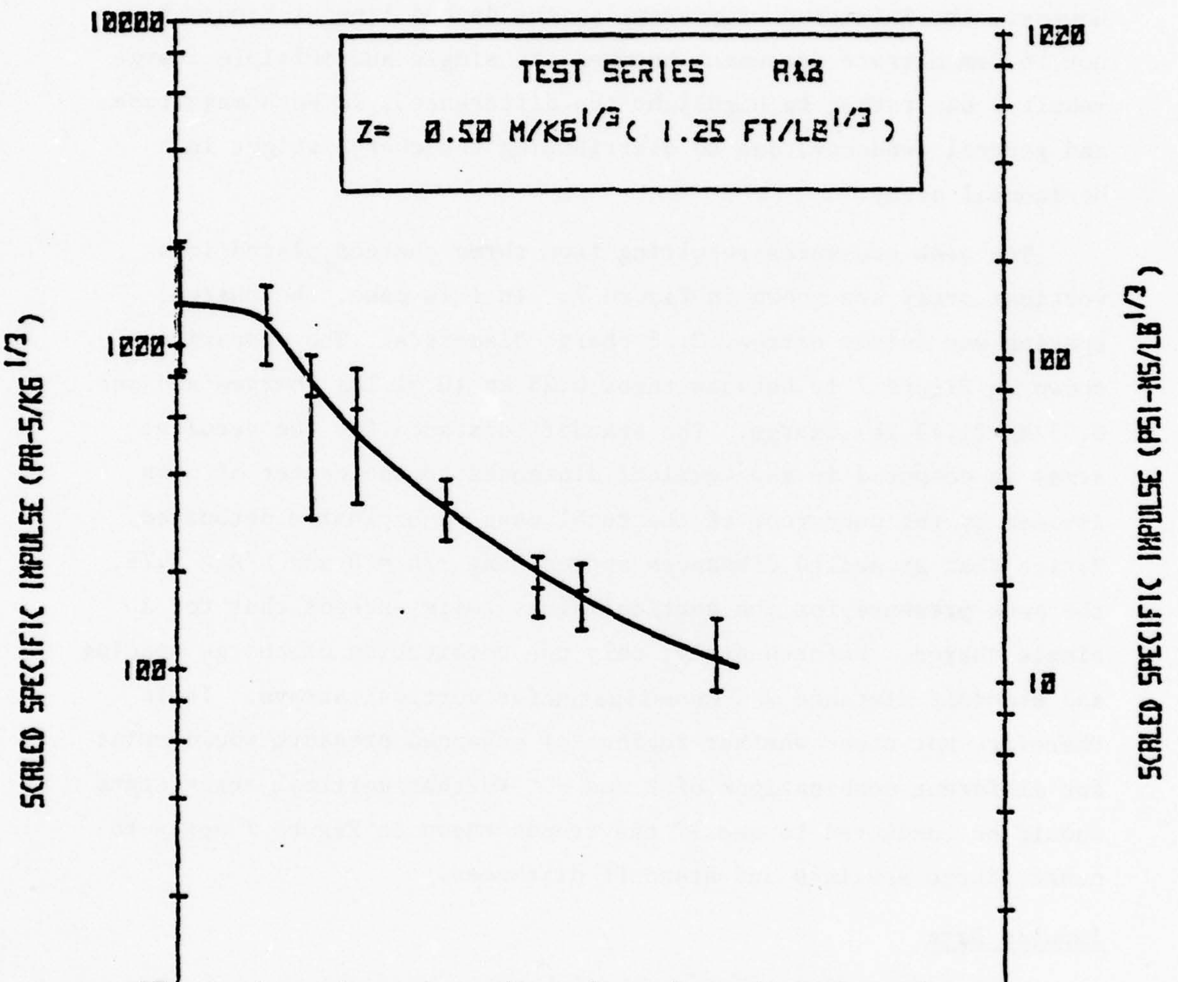

FIGURE 8. SPECIFIC IMPULSE FOR SINGLE CHARGE TEST SERIES A & B.

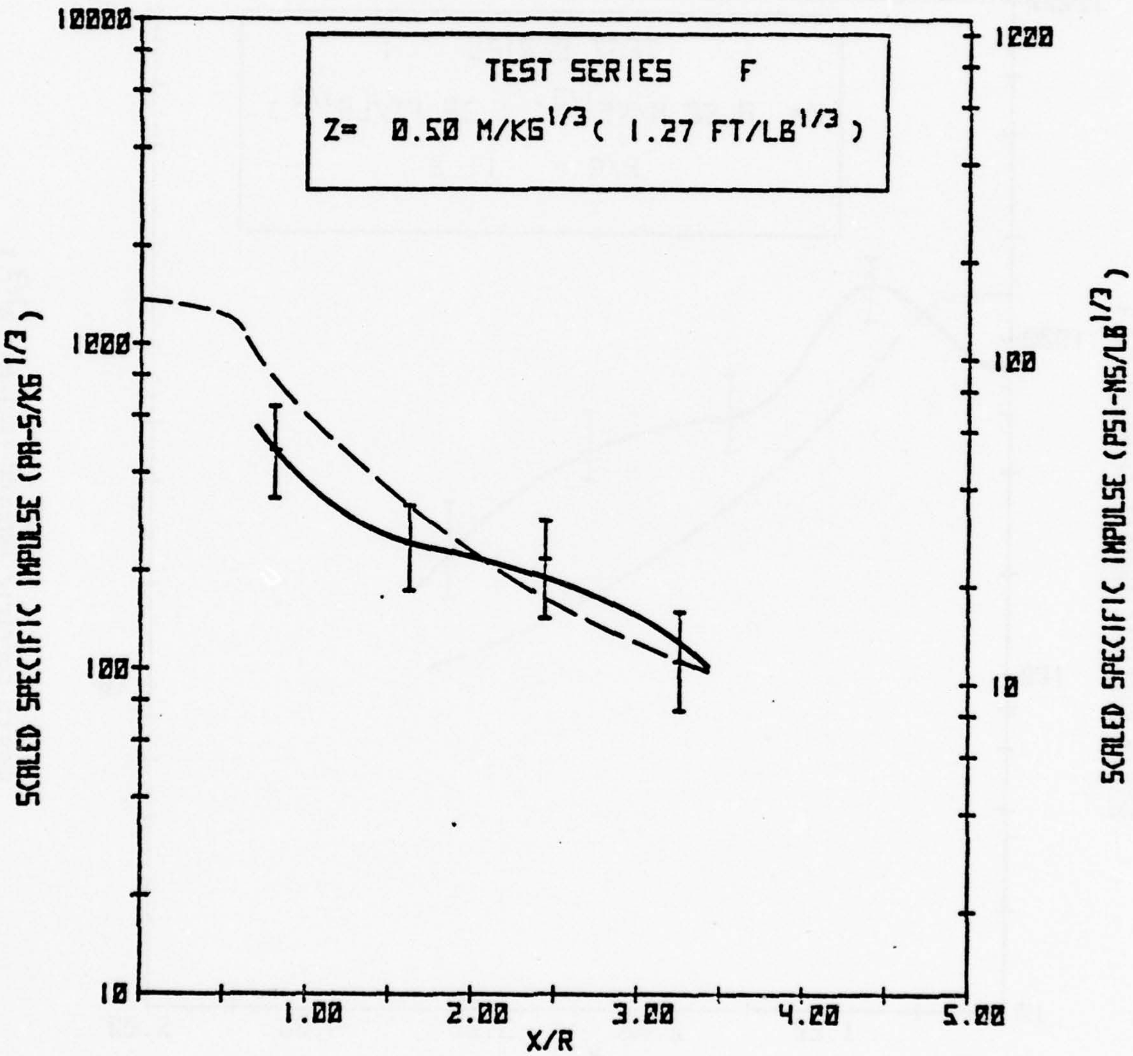

FIGURE 9. SPECIFIC IMPULSE FOR GROUPED ARRAY TEST SERIES F.

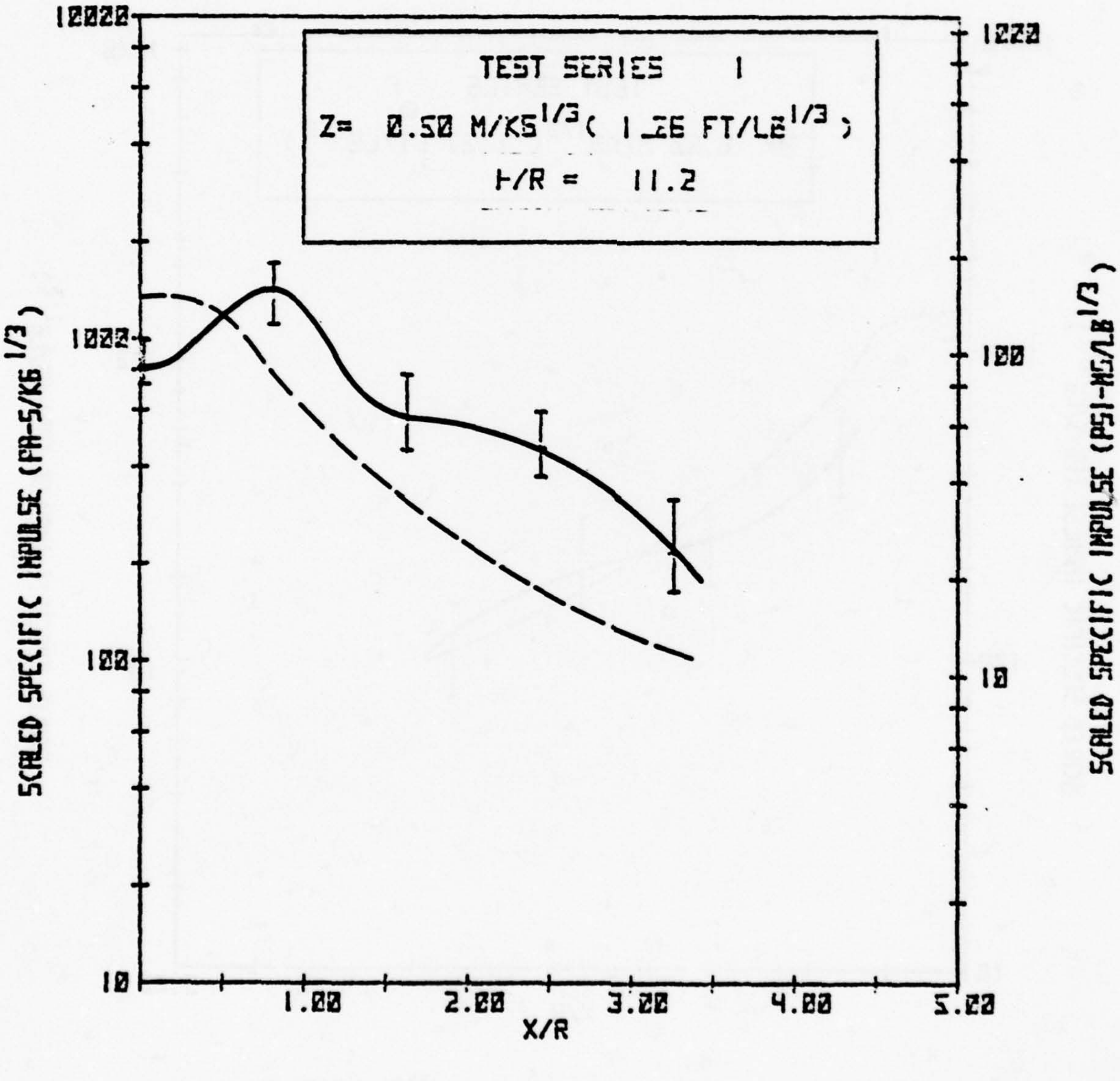

FIGURE 10. SPECIFIC IMPULSE FOR HORIZONTAL ARRAY TEST SERIES I.

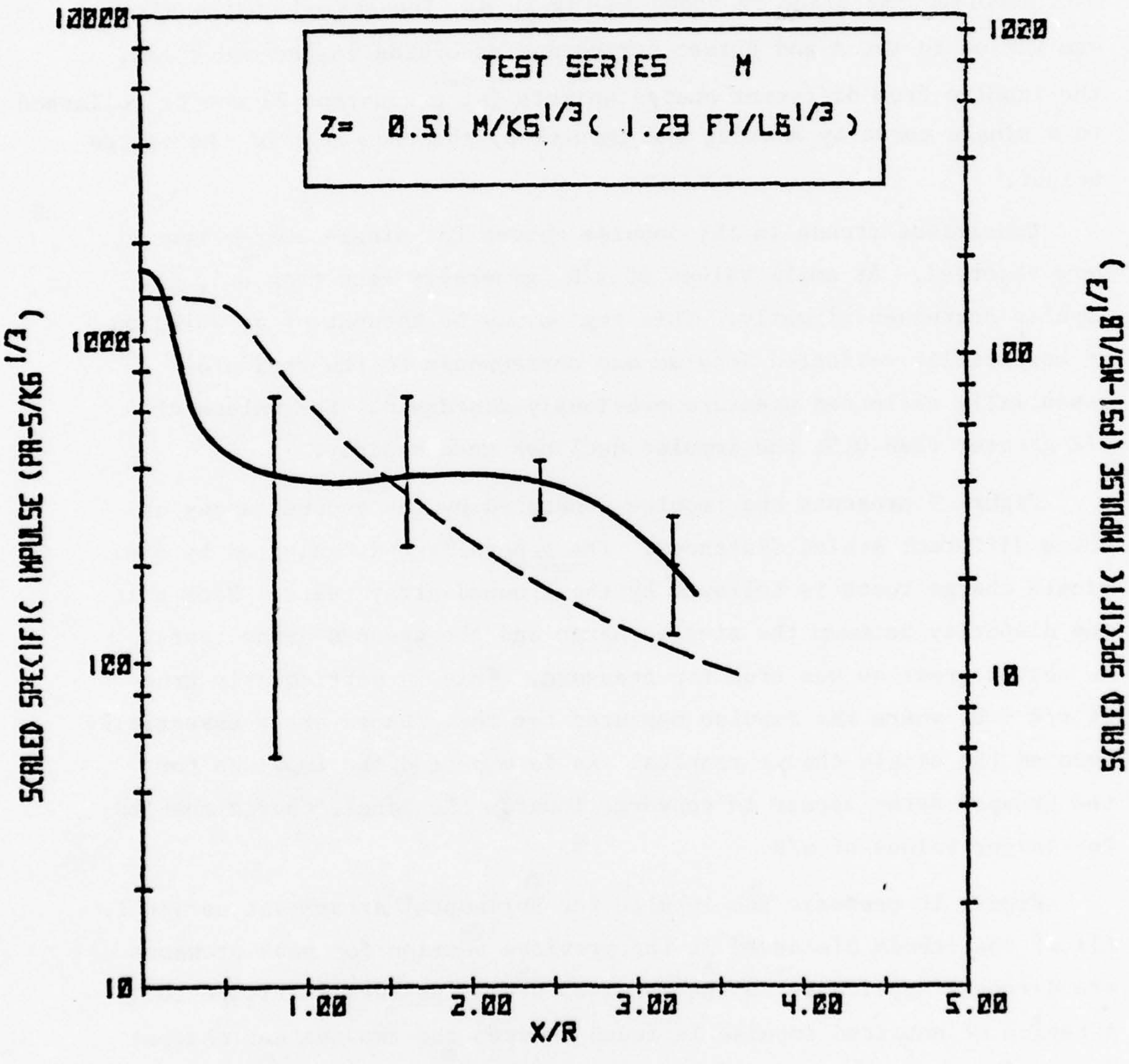

FIGURE 11. SPECIFIC IMPULSE FOR VERTICAL ARRAY TEST SERIES M.

the minimum to the maximum value recorded at a given value of x/R, is generally larger for impulse than for peak pressure. Several factors contribute to the larger scatter, including thermal drift and uncertainties in determining the positive duration. The impulse for a single charge at a scaled distance of 0.5 $m/kg^{1/3}$ (1.25 $ft/lb^{1/3}$) from a reflecting plane is shown in Figure 8. The scaled charge size was varied in the A and B test series and according to the model law, the impulse from different charge weights (at a constant Z) can be collapsed to a single curve by scaling the impulse by the cube root of the charge weight.

Consistent trends in the impulse curves for single charge tests were observed. At small values of x/R, generally less than 0.5, the impulse decreases slightly. This region may be thought of as a region of essentially reflected impulse and corresponds to the region of essentially reflected pressure previously discussed. For values of x/R greater than 0.5, the impulse declines more rapidly.

Figure 9 presents the impulse generated by the grouped array at three different scaled distances. The general trend exhibited by the single charge tests is followed by the grouped array tests. Note that the disparity between the single charge and the grouped array tests is not as great as was true for pressure. This is particularly true at x/R = 0, where the impulse measured for the grouped array essentially equaled the single charge results. As is expected, the impulses for the grouped array appear to converge towards the single charge results for larger values of x/R.

Figure 10 presents the impulse for horizontal array test series I. All of the trends discussed in the previous section for peak pressure are directly applicable to the impulse curve. As seen in Figure 10, a region of enhanced impulse is found between the two nearest charges. This region of enhanced response is more pronounced than for pressure (Figure 6). The enhanced impulse is probably caused partially by the contribution to the impulse from the third charge and by a slight elongation of the positive duration.

The impulse resulting from three charges placed in a vertical array are shown in Figure 11. The variations in impulse with x/R is virtually the same as for pressure (Figure 7), and therefore the comments made in the section for pressure are directly applicable to Figure 11.

SUMMARY

A total of 44 tests was conducted at scaled distances ranging from 0.335 m/kg$^{1/3}$ (0.84 ft/lb$^{1/3}$) to 1.18 m/kg$^{1/3}$ (3.0 ft/lb$^{1/3}$). Four different charge geometries were studied: single charges, and grouped, horizontal and vertical arrays. Based on the results of these tests the following observations can be made:

- The pressure and impulse for grouped arrays at small scaled distances is lower than for single charges. The disparity between grouped array and single charge pressure is more pronounced than for impulse.

- For horizontal arrays, regions exist where the pressure and impulse exceed what would be expected from a single charge. The location of maximum response is dependent on the charge spacing and the standoff distance, but generally is found halfway between charges. Other regions of enhanced pressure and impulse exist just beyond the outside charge. For very wide charge spacings, the pressure and impulse are nearly constant over the entire range in x/R. For very narrow charge spacings, the regions of enhanced pressure are less pronounced than for intermediate charge spacings.
- Only one combination of charge spacings and standoff distances was investigated for vertical arrays. The results indicated that two regions of enhanced pressure and impulse exist: one directly under the vertical array and another for x/R > 1.5.

- The tests conducted verified the expectation that at large scaled distances, the blast parameters measured for multiple charges could approach those of a single charge. The distance at which the curves begin to coalesce is apparently the greatest for widely spaced horizontal arrays and the smallest for grouped arrays.

Although the scaling law has not been verified for multiple detonations, the measurements in this paper can be used to obtain a more rational design for munition processing plants. Caution should be exercised, however, when extrapolation of these results is required beyond the scaled distances, positions, or charge sizes tested.

REFERENCES

1. J. C. Hokanson, E. D. Esparza, A. B. Wenzel, "Measurement of Blast Parameters on a Barricade Due to Simultaneous Detonations of Multiple Charges," Final Report for Contract DAAA21-76-C-0254, SwRI Project No. 02-4600, July 15, 1977.

2. "Structures to Resist the Effects of Accidental Explosions," Department of the Army Technical Manual TM5-1300, June 1969, pp. 465.

AIR BLAST ENHANCEMENT FROM MULTIPLE DETONATIONS

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Aberdeen Proving Ground, MD

ABSTRACT

The damaging parameters from single explosions have been studied and discussed in many reports. Far less attention has been given to the detonation of multiple charges. This paper will review the work that has been done to better understand the enhancement of damage that can result from multiple detonations. This paper will review multiple detonations from two to twenty-four charges and both simultaneous and non-simultaneous detonations.

Analytical prediction techniques will be compared with the actual measurements. In the multiple charge case, the overpressure is enhanced at the expense of the dynamic pressure, thus resulting in damage at greater distance than if the total explosive weight had been detonated as a single charge.

AIR BLAST ENHANCEMENT FROM MULTIPLE DETONATIONS

With the increased concern over multiple explosions, it became apparent that additional information was required to better understand the phenominology associated with both simultaneous and non-simultaneous detonations. Several small scale tests were conducted in 1960 at the Ballistic Research Laboratory (BRL)[1] to establish the enhancement in air blast coverage on the ground that can be obtained from the simultaneous detonations of a cluster of explosive charges as compared to the detonation of a single large charge. In those early studies it was shown, using trios of bare explosive spheres located on the vertices of an equilateral triangle, that efficient use of such simultaneously detonated charges requires an optimization of the separation distance between charges and their height of burst to obtain maximum coverage on the ground with a given overpressure. Particular emphasis had been placed on developing iso-pressure contours for specific pressure levels in and about the triad for both ground and air bursts.

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[1] *Armendt, B. F., Hippensteel, R. G., Hoffman, A. J., and Kingery, C. N. "The Air Blast from Simultaneously Detonated Explosive Spheres" Aberdeen Proving Ground: Ballistic Research Laboratories Memorandum Report No. 1294, August 1960 (UNCLASSIFIED).*

Several phenomenological aspects of the blast problems associated with simultaneous detonations remained uncertain at the completion of the small scale studies. Therefore, it was felt by the Air Force Special Weapons Center (AFSWC) and the BRL that a larger scale test should be conducted. Consequently a larger scale test was considered with the following airblast objectives: (1) to determine the dynamic pressure field both within and outside a triad of charges, (2) to determine more precise mapping of the peak overpressure field in the region close to the center of the charges and in other regions of reflection enhancement. The test site selected for the program was White Sands Missile Range, New Mexico. The nickname "White Tribe", an acronym derived from White Sands Triple Burst Experiment, was selected. The test conditions were scaled from the previous 454g and 3.6kg charges fired to give the optimum separation of a triangular array, for ground bursts, for the case of maximizing ground coverage with peak pressure exceeding 689.5 kPa. Thus, a nominal separation of 53.6 metres between each of three 4536 kg bare charges of Pentolite was selected. Moreover, these conditions could simulate those predicted for the simultaneous detonation of three 200 KT nuclear weapons at a separation of approximately 1463.0 metres.

The air blast in and about the triad of explosive charges was measured at a large number of stations using several different techniques. A total of 29 piezoelectric gages of BRL design, 27 strain gages and 43

mechanical self-recording pressure transducers were used. Several motion picture and still cameras were used to observe the detonation from both the ground and from the air.

A day or two before the three tests, when all instrumentation was nearly ready, the large explosive charges were prepared at the vertices of the triangle. The explosive was TNT, formed in 3.6 kg blocks, and stacked in an hemispherical shape to yield an air blast equivalent to that from a 4536 kg charge of 50/50 Pentolite at sea level conditions. So the charges weighed 5248 kg in order to compensate for the 1220 metre elevation of the White Sands site.

With the exception of several variations in the location of gages, each of the White Tribe firings was conducted in essentially the same manner and yielded similar results. The side-on overpressure contour plot for the first shot is shown in Figure 1. From these results it can be seen that by dividing the charge into three approximately equal portions and then detonating them simultaneously that the area on the ground covered by at least 689.5kPa is increased by 55% over the coverage that would have been obtained if the total quantity of explosive had been left in one charge. Mapping of the dynamic overpressure field was not accomplished, although some of the expected dynamic pressure phenomena were observed.

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[2] *Armendt, B. F., Hippensteel, R. G., Hoffman, A. G., and Keefer, J. H., "Project WHITE TRIBE: Air Blast from Simultaneously Detonated Large Scale Explosive Charges". BRL Report 1145 September 1961.*

A better understanding of the airblast environment surrounding a two charge multiburst detonation above the ground was gained through an experimental research program known as DIPOLE WEST. This series of 16 experiments was conducted at the Defense Research Establishment, Suffield, Alberta, Canada during the period of June 1973 to August 1975.

These experiments were designed to provide: (1) The verification, to the extent possible, of the validity of the Low Altitude Multiburst (LAMB) blast model for predicting the free field blast environment produced by multiple nuclear explosions occurring in close time and space proximity, (2) Empirical information suitable for the development of a multiple fireball interaction and cloud rise model, (3) Reliable Blast data with which to establish or confirm height-of burst effects in the high pressure region for ideal, near ideal, and non-ideal surface conditions.

Specific experimental and analytical objectives were to examine the air blast phenomenology of strong shock on shock, shock on fireball, and fireball flow interactions from the simultaneous and non-simultaneous detonation of multiple (two) high explosive charges. Density, particle velocity, stagnation pressure and overpressure were measured at and near the ground surface as well as at and near the ideal reflecting plane (midway between charges) with electronic pressure instrumentation and high speed photography[3]. A photograph of Shot 11 fireballs at 0.05 seconds after detonation is shown in Figure 2.

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[3] *Dewey, J. M. et al, "Photogrammetry of the Shock Front Trajectories on Dipole West Shots 8, 9, 10, and 11," DNA 3777F, University of Victoria, B. C., Canada V8W2Y2, July 1975.*

Comparison of maximum overpressure from the 15.2 metre vertical separated events (Shot 8 and 11) with calculational results produced by the Air Force Weapons Laboratory. HULL code results are presented in Figure 3. Correlation between the two is good.[4,5,6]

DIPOLE WEST experimental data was successfully acquired on the rise and expansion of fireballs and on the interaction of shock waves generated by the detonation of simultaneous and non-simultaneous multibursts. The path of the triple point and the Mach stem region were identified.

The MISERS BLUFF Test Series was developed to address the problem of multiburst phenomena. This program was divided into two phases. Phase I consisted of a series of eight experiments conducted at White Sands Missile Range, New Mexico during July to December 1977.

Test configurations for the eight Phase I experiments are summarized in Table 1.

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[4] *Keefer, John H. and Reisler, Ralph E., "Multiburst Environment - Simultaneous Detonations," Project Dipole West, BRL Report No. 1766, March 1975, USA Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland 21005.*

[5] *Reisler, Ralph E. and Pettit, Burnett A., "Project Dipole West - Multiburst Environment (Non-Simultaneous Detonations), "BRL Report No. 1921, September 1976, USA Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland 21005.*

[6] *Needham, C. E. and Wittmer, L. A., "The Air Force Weapons Laboratory Low Altitude Multiple Burst (LAMB) Model," AFWL-DYT-75-2 (Unpublished).*

Table 1. Phase I Test Summary

	Event No. 1	2	3	4	5	6	7	8
Individual Charge Weight, lb	1000	1000	1000	1000	1000	1000	256	1000
Charge Elevation	Half Buried	Surface Tangent	Half Buried	Surface Tangent	Tangent Below	Half Buried	Half Buried	Surface Tangent
Number of Charges	1	1	1	6	1	6	1	24
Array Configuration	-	-	-	Hexa-gonal	-	Hexa-gonal	-	Multi-Hexa-gonal
Spacing Between Charges, ft	-	-	-	70	-	120	-	70
Date Detonated, 1977	2 Aug	15 Aug	23 Aug	7 Sep	22 Sep	13 Oct	26 Oct	7 Dec

Multiburst Event 4 consisted of an array of six 4540kg TNT charges in an equally spaced hexagonal configuration as shown in Figure 4. Individual charges were placed tangent to the ground surface on a 21.3 metre. Event 8 was an array of 24 charges placed in a multi-hexagonal geometry as shown in Figure 5. The charges were surface tangent and placed on 21.3 metre spacings like Event 4. The air blast predictions for Event 8 are presented in Figure 6 and 7. The small circles are the measurements. The over all agreement was good.

Phase II consisted of two experiments conducted at Planet Ranch Site in west-central Arizona on 28 June and 30 August 1978. The first event was a single charge of 109,000 kg ammonia nitrate/fuel oil (ANFO).

The ANFO was stacked on the surface of the ground in the shape of a vertical cylinder with a hemispherical cap. The second event was six charges each similar to event one and placed in a hexagonal array. The spacing was 100 metre between charges.

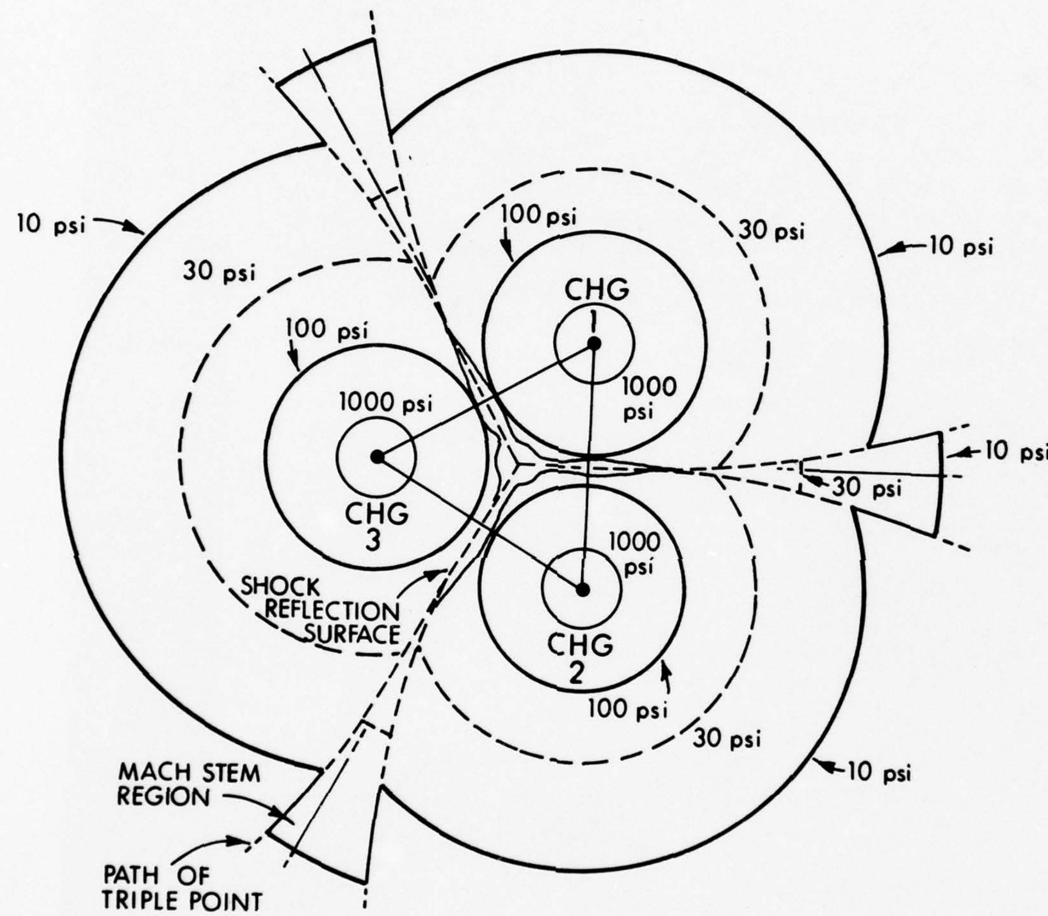

Figure 1 Overpressure Contours

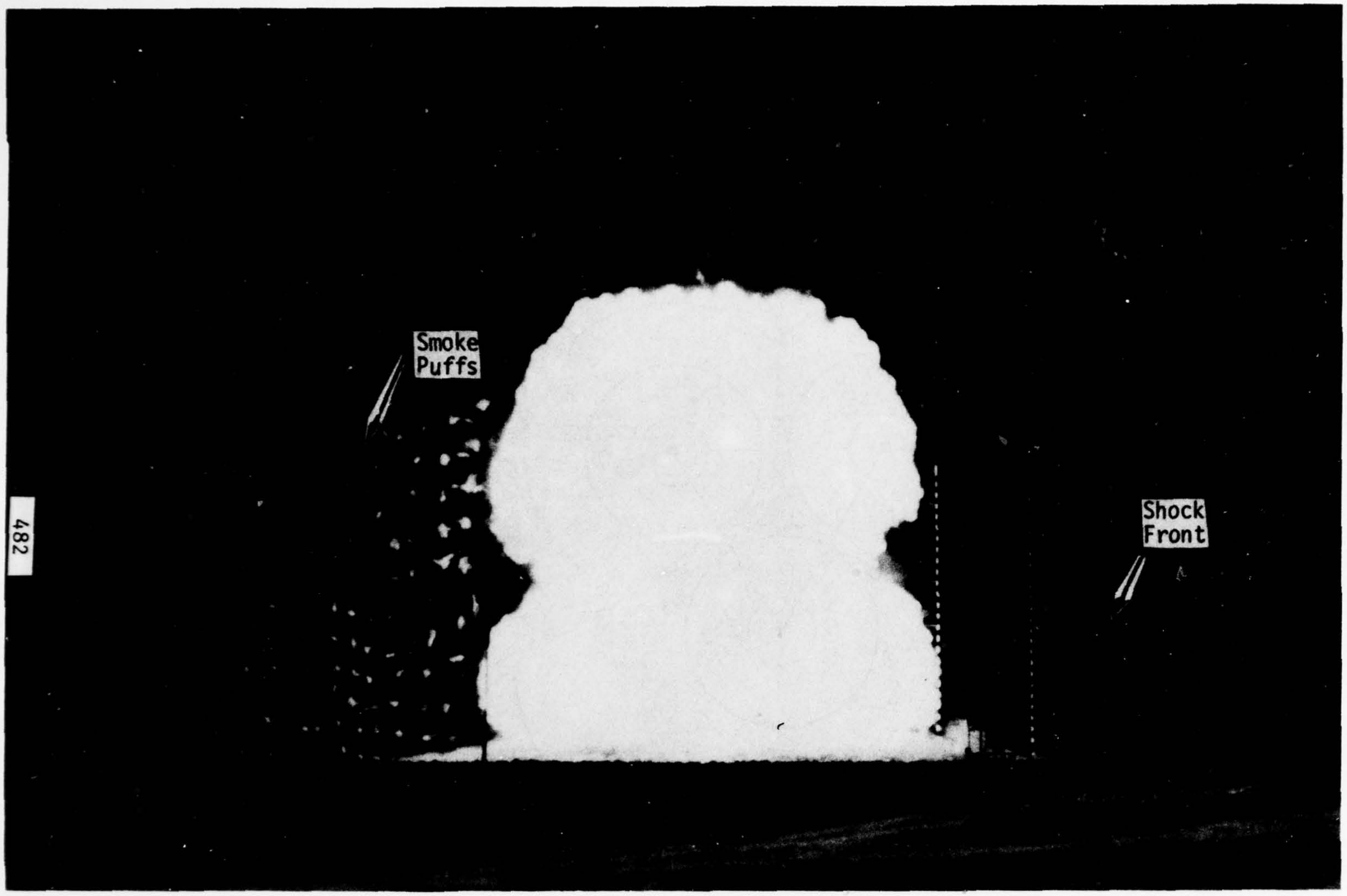

Figure 2 Fireballs at 0.05 Second After Detonation

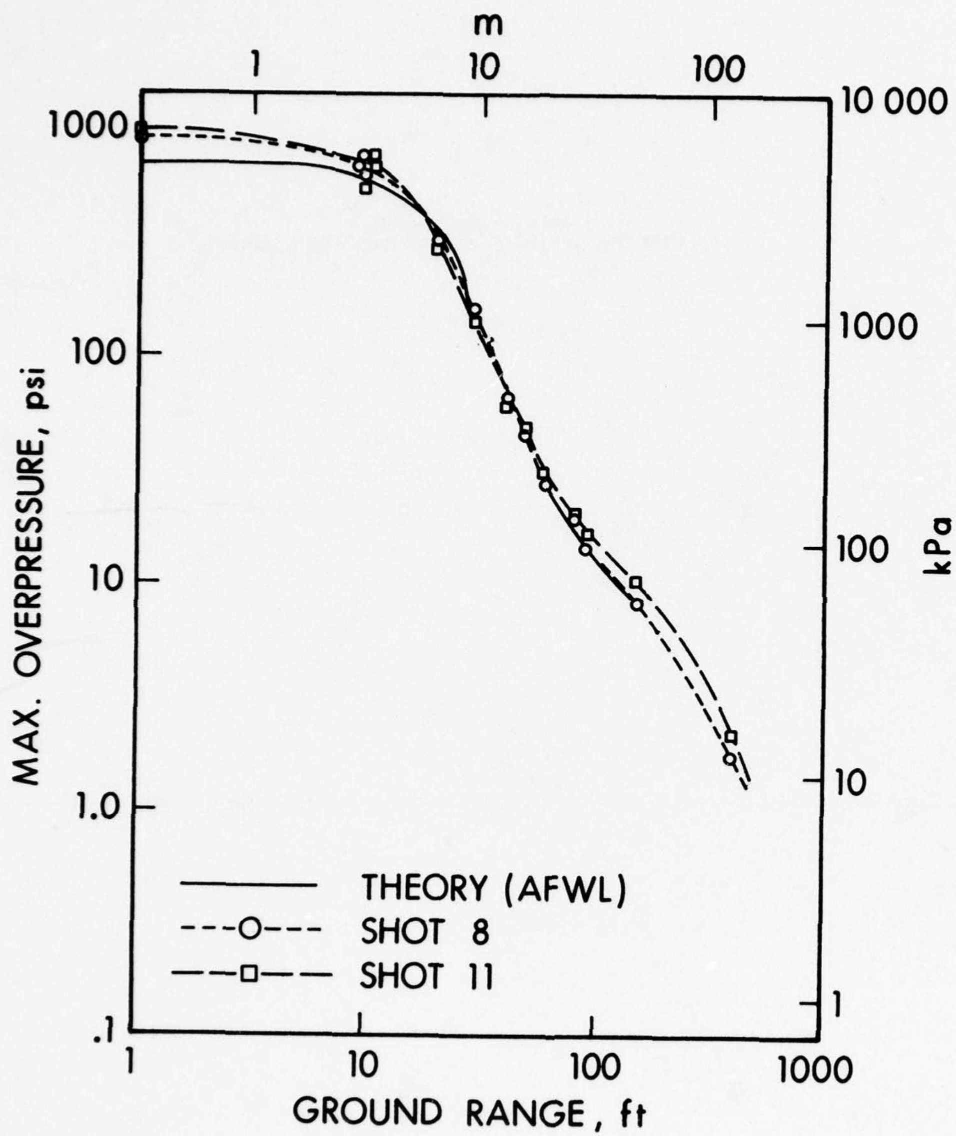

Figure 3 Comparison of Calculated and Experimental Maximum Overpressure at Ground Level

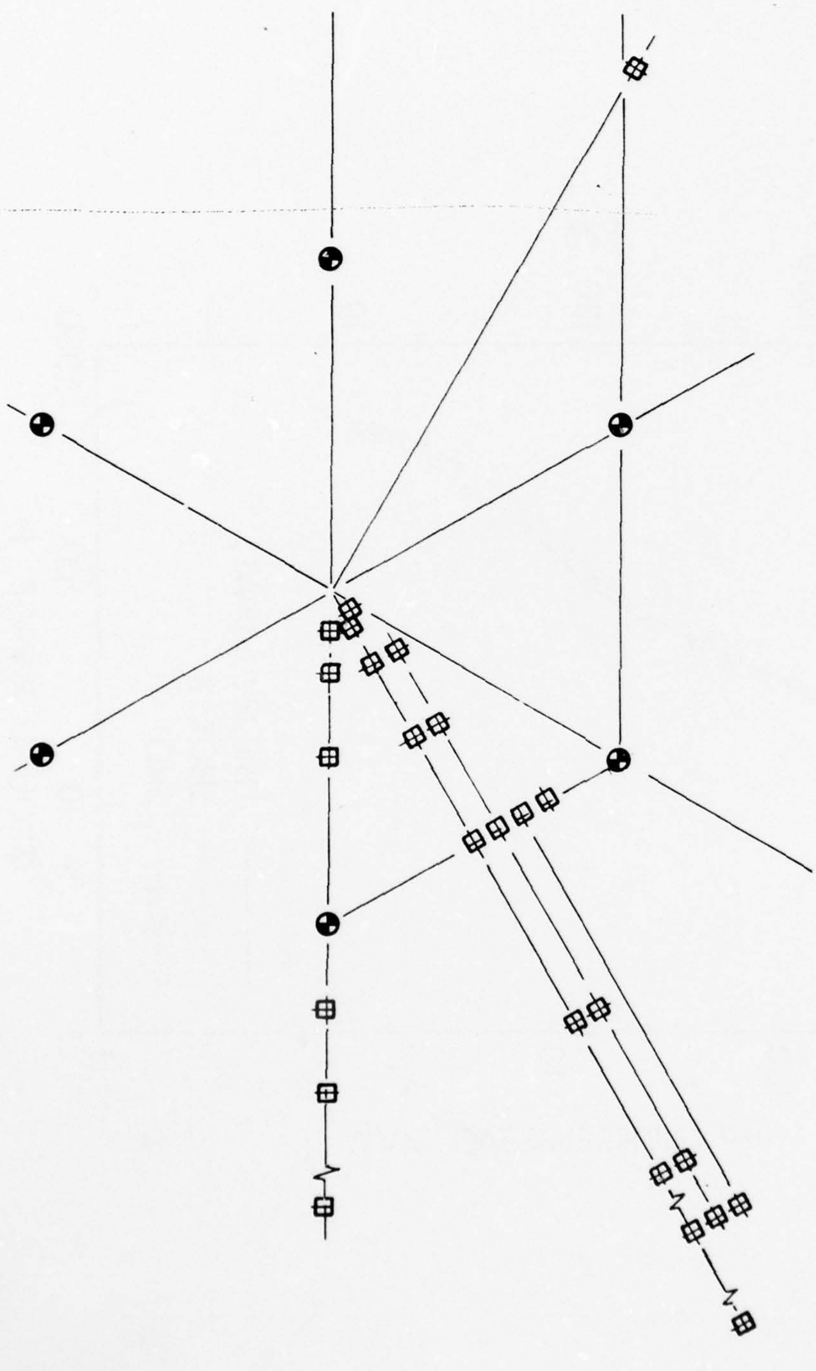

Figure 4 Six Charges and Airblast Gages Layout for Misers Bluff Event I-4

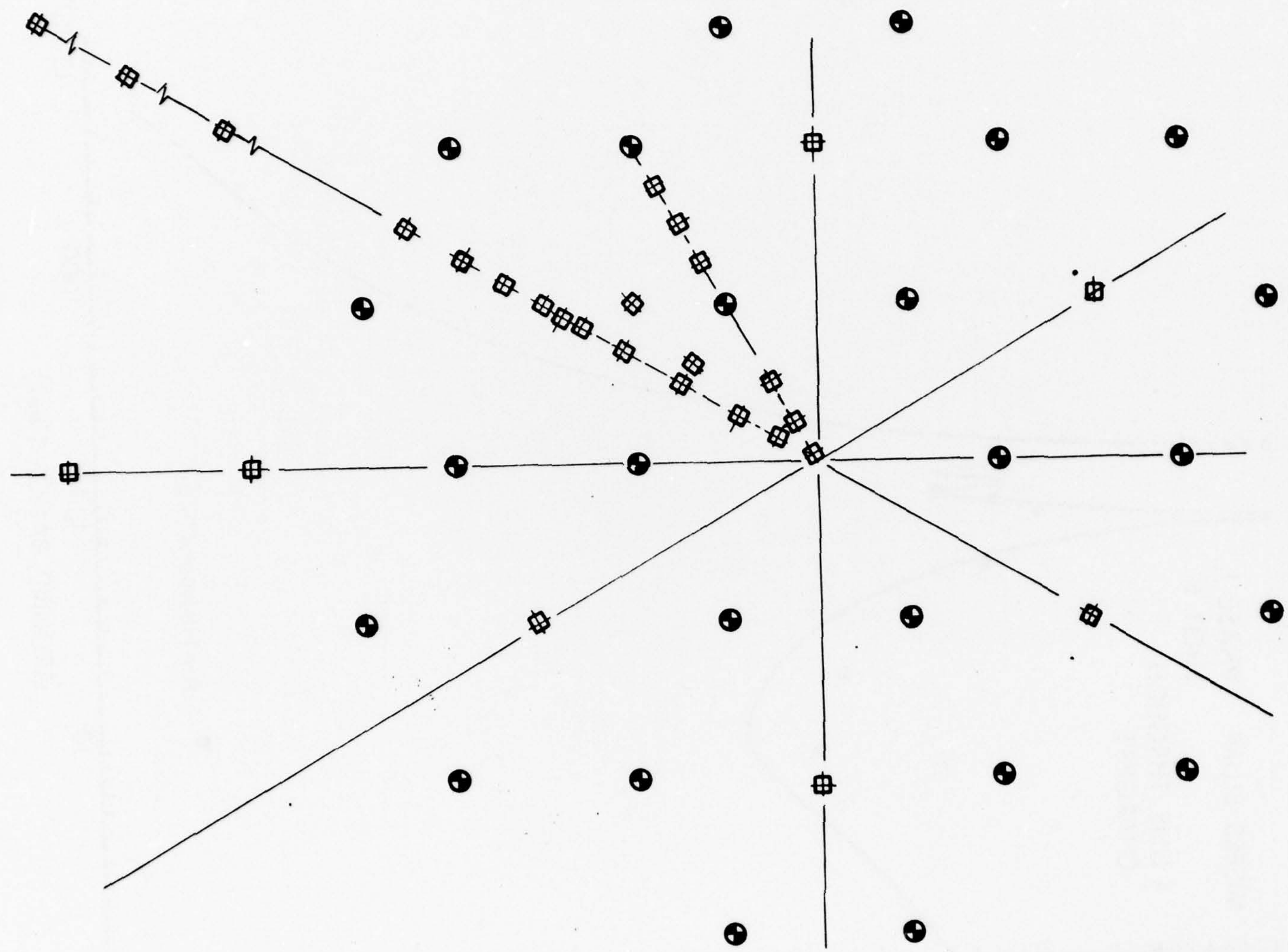

Figure 5 Twenty Four Charges and Airblast Gages Layout for MISERS BLUFF Event I-8

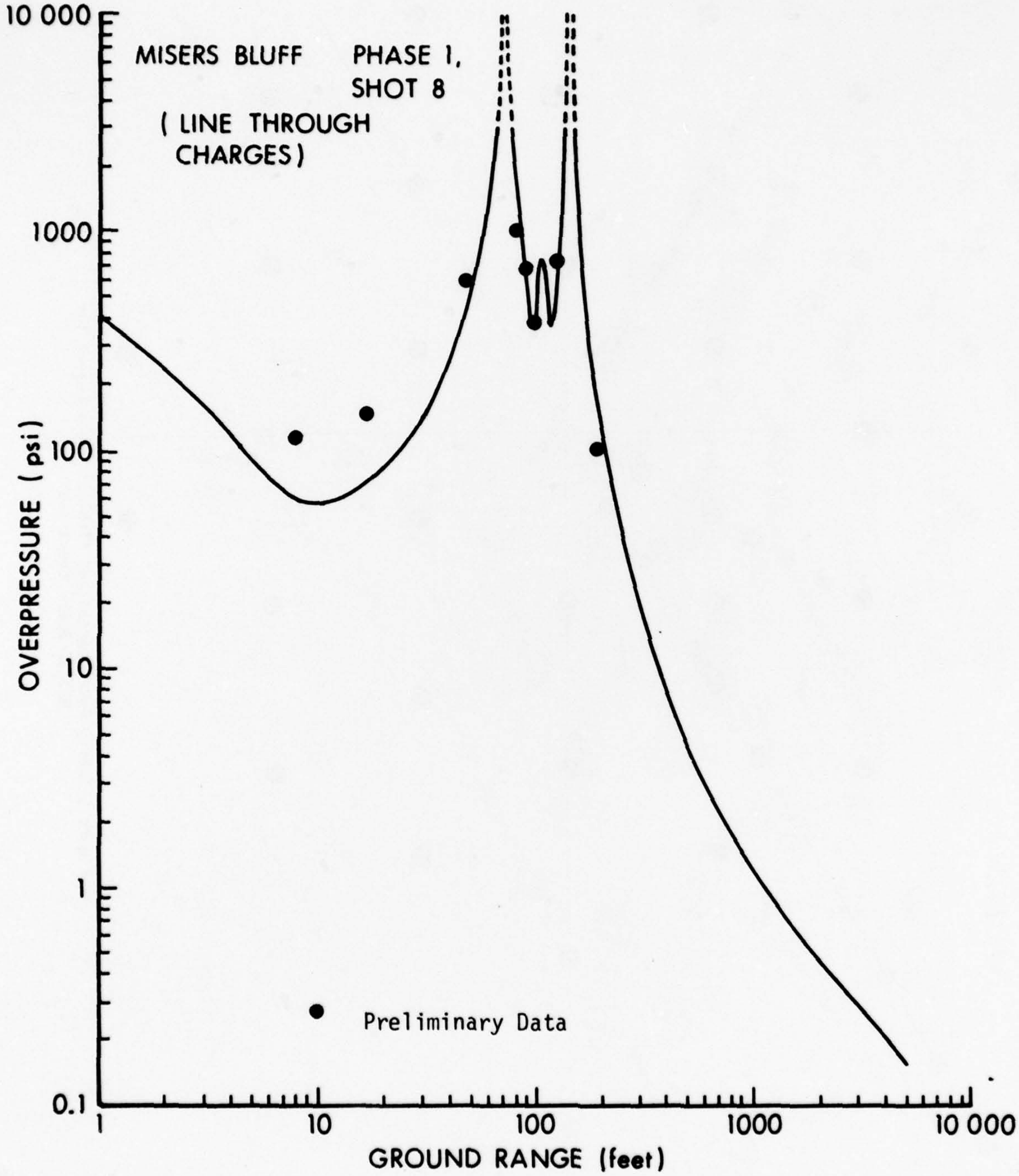

Figure 6 Airblast Predictions Compared with Measurements on a Line Through Charges

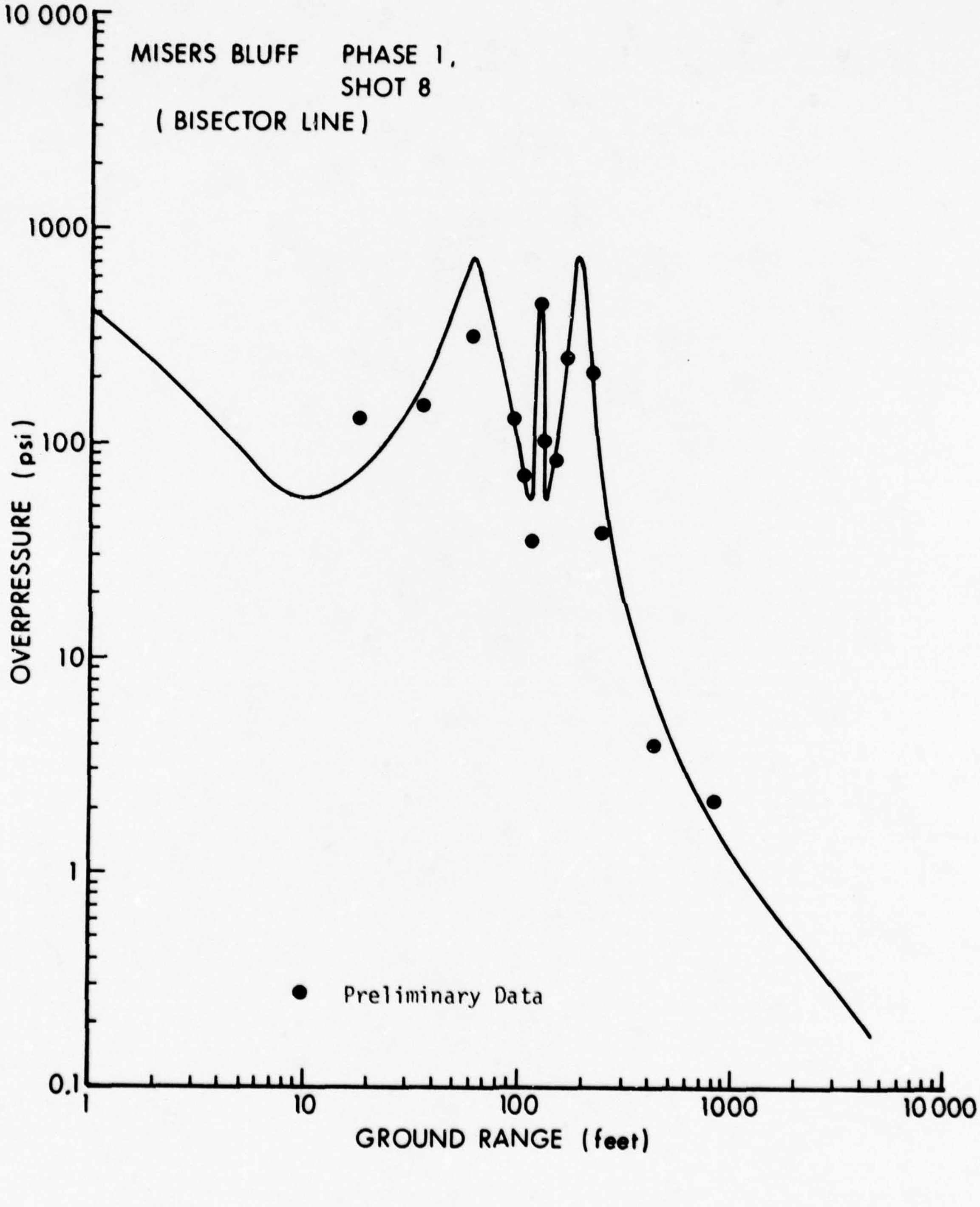

Figure 7 Airblast Prediction Compared with Measurements on a Bisector Line

LONG RANGE (LOW PRESSURE) AIRBLAST PARAMETERS

by

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INTRODUCTION

The discussion of long range airblast parameters is of continuing interest. Reed[1] defines low overpressures from explosions as those well below the eardrum injury threshold of 35 kPa (5 psi). At this level the environmental concern is primarily with minor damage thresholds, rather than annoyance with single events. Reed further states[1] that blast wave analyses, rather than acoustic analyses, should be used when sound pressure levels are above 200 Pa (140 dB or 0.03 psi).

Though this interest in low overpressures from explosions continues, there is not a great deal of experimental, quasi-experimental, or even theoretical data detailing such information as maximum underpressure, negative phase duration, or negative phase impulse. This paper will present the results of a limited literature search in this area, as well as new experimental data generated at NSWC. The results span the pressure range of 20 kPa down to 300 Pa.

The results presented here are applicable to surface and near-surface bursts only. However, in conducting the literature search, this restriction was not placed. Any data pertaining to free air explosions were converted to surface bursts using a standard 2W correction.

BIBLIOGRAPHIC MATERIAL

Nine basic sources of data were uncovered as a result of the literature search. These nine sources are presented in Table 1. Three of them are of major importance. These are Granstrom, Potter and Jarvis, and the new ANSI standard.

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1 Reed, Jack W., "Guidelines for Environmental Impact Statements on Noise (Airblast)," in Minutes of the Seventeenth Explosives Safety Seminar, 14-16 Sep 1976; pp. 502-509.

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DATA MANIPULATION

All of the data acquired during the literature search were converted to equivalent TNT data using tables of equivalent weight presented in Reference (10). The data located during the literature search were fitted by the method of least squares and are presented in the following sections.

RECENT DATA

Measurements were recently completed at NSWC on a series of 540 kilogram (TNT equivalent) charges detonated at heights of 1.52 and 3.05 meters above the surface. Measurements were made along three radial directions from surface zero out to a distance of 4350 meters. These data will appear on the graphs of each of the airblast parameters presented in the following sections.

LONG RANGE AIRBLAST PARAMETERS

Figure 1 shows both an "ideal" and a "real" airblast wave. The significant differences between the two include the finite rise-time of the real wave, the existence of a secondary shock located in the negative phase, and the oscillation of the pressure as it approaches ambient pressure. Basic airblast parameters are also shown in Figure 1.

The following parameters (scaled to sea level conditions -- for other conditions, use the scaling techniques presented in Reference (10)) will be considered in this paper: (1) time of arrival of the main shock wave, TOA, (2) peak positive overpressure, Δp^+, (3) maximum underpressure, Δp^-, (4) peak-to-peak pressure, P_k, (5) peak pressure of the secondary shock, P_{ss}, (6) positive duration, τ^+, (7) positive impulse, I^+, (8) negative duration, τ^-, and (9) negative impulse, I^-.

The SI system of units has been used throughout this paper. In addition, all data are presented in terms of scaled distance (λ) defined as distance in meters divided by the cube root of the charge weight in kilograms ($m/kg^{1/3}$).

TIME OF ARRIVAL

Shock wave time of arrival is defined as the time required for the shock wave to transit the distance from the center of

(10) Swisdak, Michael M., "Explosion Effects and Properties: Part I--Explosion Effects in Air," NSWC/WOL/TR 75-116, 6 October 1975.

the explosion to the point at which the measurement is to be made. Three sources of information were located in the literature and these are presented below:

$$TOA = 0.8854\ W^{1/3}\ \lambda^{1.4979 - 0.05071 \ln\lambda} \quad (1)\ \text{POTTER \& JARVIS}$$

$$TOA = 1.1808\ W^{1/3}\ \lambda^{1.2410} \quad (2)\ \text{GRANSTROM}$$

$$TOA = 0.9772\ W^{1/3}\ \lambda^{1.4505 - 0.04741 \ln\lambda} \quad (3)\ \text{KINGERY}$$

where λ is scaled distance in $m/kg^{1/3}$, W is charge weight in kilograms, and TOA is time of arrival in milliseconds (ms). Equations (1), (2) and (3) are plotted in Figure 2.

PEAK POSITIVE OVERPRESSURE

Peak positive overpressure is the maximum pressure above ambient pressure produced by a blast wave. Five sources of data were found for this parameter, and are presented below:

$$\Delta p^+ = 289.7\ \lambda^{-1.257} \quad (4)\ \text{POTTER \& JARVIS}$$

$$\Delta p^+ = 261.7\ \lambda^{-1.223} \quad (5)\ \text{GRANSTROM}$$

$$\Delta p^+ = 425.5\ \lambda^{-1.407} \quad (6)\ \text{KINGERY}$$

$$\Delta p^+ = 431.2\ \lambda^{-1.42} \quad (6b)\ \text{Sadwin and Christian}$$

$$\Delta p^+ = 150.2\ \lambda^{-1.1} \quad (7)\ \text{ANSI STANDARD}$$

$$\Delta p^+ = 250.3\ \lambda^{-1.33} \quad (8)\ \text{UTE}$$

where Δp^+ is positive overpressure in kilopascals (kPa), and λ is scaled distance as defined above. These equations are plotted in Figure 3.

MAXIMUM UNDERPRESSURE

Maximum underpressure is the lowest pressure below ambient pressure produced by a blast wave. From hydrodynamic considerations, the slope of the $\log(\Delta p^-)$ vs $\log(\lambda)$

curve should be -1. Experimentally determined values are very close to this. The following expressions are determined from the literature:

$$\Delta p^- = 46.48\ \lambda^{-1.054} \qquad \text{(9) POTTER \& JARVIS}$$

$$\Delta p^- = 38.89\ \lambda^{-0.961} \qquad \text{(10) GRANSTROM}$$

$$\Delta p^- = 46.19\ \lambda^{-0.972} \qquad \text{(11) NUCLEAR}$$

where Δp^- is in kilopascals (kPa) and λ as defined above. These are plotted in Figure 4.

PEAK-TO-PEAK PRESSURE

Peak-to-peak pressure is defined as the sum of the absolute values of the peak positive overpressure and the maximum underpressures. The following expressions were derived from the literature:

$$P_k = 360.97\ \lambda^{-1.249} \qquad \text{(12) POTTER \& JARVIS}$$

$$P_k = 281.97\ \lambda^{-1.151} \qquad \text{(13) GRANSTROM}$$

where P_k is in kilopascals (kPa) and λ is defined above.

Reference (5) states that at "long range" P_k can be approximated as $2\Delta p^+$, without defining long range. If we consider the equations in the last three sections for Δp^+, Δp^-, and P_k, it can be shown that this is not the case. Over the range of validity of these equations, a better approximation for P_k is $1.28\Delta p^+$. Equations (12) and (13) are shown plotted in Figure 5.

PEAK PRESSURE IN THE SECOND SHOCK

A secondary shock, sometimes referred to as a "Wecken Shock", often appears on the airblast waves produced by high explosives. At pressures below about 140 kPa, this second shock becomes very apparent, usually appearing during the negative phase of the blast wave. Two sources of information were located in the literature:

$$P_{ss} = 93.67\ \lambda^{-1.446} \qquad \text{(14) POTTER \& JARVIS}$$

$$P_{ss} = 95.79\ \lambda^{-1.381} \qquad \text{(15) SADWIN \& SWISDAK}$$

where P_{ss} is the peak pressure in the second shock in kilopascals (kPa) and λ is defined as above. These equations are plotted in Figure 6.

POSITIVE DURATION

Positive shock wave duration is defined as the length of time (measured from the first pressure rise) necessary for the overpressure to return to the ambient pressure. Four sources of information were located:

$$\tau^+ = 2.239\ W^{1/3}\ \lambda^{0.302} \quad (16)\ \text{POTTER \& JARVIS}$$

$$\tau^+ = 1.653\ W^{1/3}\ \lambda^{0.5470-0.0422\ln\lambda} \quad (17)\ \text{GRANSTROM}$$

$$\tau^+ = 1.0507\ W^{1/3}\ \lambda^{0.8393-0.0825\ln\lambda} \quad (18)\ \text{ANSI STANDARD}$$

$$\tau^+ = 2.100\ W^{1/3}\ \lambda^{0.4048-0.0199\ln\lambda} \quad (19)\ \text{KINGERY}$$

where τ^+ is positive duration in milliseconds (ms), W is charge weight in kilograms (kg), and λ is scaled distance as defined above. These equations are plotted in Figure 7.

POSITIVE IMPULSE

Positive impulse is defined as the area under the positive phase of the pressure-time curve; i.e.,

$$I^+ = \int_0^{\tau+} P(t)dt$$

where τ^+ is the positive phase duration. Four sources were found for positive impulse; these are shown below:

$$I^+ = 228.667\ W^{1/3}\ \lambda^{-0.866} \quad (20)\ \text{POTTER \& JARVIS}$$

$$I^+ = 259.153\ W^{1/3}\ \lambda^{-0.7837-0.0286\ln\lambda} \quad (21)\ \text{GRANSTROM}$$

$$I^+ = 367.125\ W^{1/3}\ \lambda^{-1.0801+0.0072\ln\lambda} \quad (22)\ \text{ANSI STANDARD}$$

$$I^+ = 228.214\ W^{1/3}\ \lambda^{-0.7902-0.0328\ln\lambda} \quad (23)\ \text{KINGERY}$$

where I^+ is positive impulse in pascal-seconds (Pa-s), W is charge weight in kilograms (kg), and λ is scaled distance as defined above. These equations, with the exception of equation 23, are shown plotted in Figure 8. Over the scaled distance range of 15-200 $m/kg^{1/3}$, equation 23 is not distinguishable from equation 22 on the graph.

NEGATIVE DURATION

Shock wave negative duration is defined as the time, measured from the end of the positive phase, required for the shock wave pressure to again reach ambient pressure. Three sources were located for this quantity:

$$\tau^- = 13.99\ W^{1/3} \qquad (24)\ \text{GRANSTROM}$$

$$\tau^- = 17.66\ W^{1/3} \qquad (25)\ \text{HE}$$

$$\tau^- = 19.45\ W^{1/3} \qquad (26)\ \text{NUCLEAR}$$

where τ^- is negative duration in milliseconds (ms), and W is charge weight in kilograms (kg). These three expressions are plotted in Figure 9. From these three expressions, it is evident that the negative duration is independent of the scaled distance and depends only on the charge weight (over the distance range under consideration).

NEGATIVE IMPULSE

Negative impulse is defined as the area under the negative phase of the pressure-time curve; i.e.,

$$I^- = \int_{\tau^+}^{\tau^-} P(t)dt$$

where τ^+ is the positive duration and τ^- is the negative duration. Only one source of information on this quantity was located:

$$I^- = 240.057\ W^{1/3}\ \lambda^{-0.8252-0.0172\ln\lambda} \qquad (27)\ \text{GRANSTROM}$$

where I^- is negative impulse in pascal-seconds (Pa-s), W is charge weight in kilograms (kg), and λ is scaled distance and has been previously defined. This equation is plotted in Figure 10.

SUMMARY

Equations have been presented for the various airblast parameters, with no judgements being made as to which equations were the preferred forms. In addition, the results from a limited experimental program have been presented. Based on interpretations of the analytical expressions, the available data base, and the new NSWC data, the author has determined a "best" set of equations to describe the long range airblast parameters. These are presented in Table 2. As further data become available, these "best" equations may change. Moreover, for particular uses, others may prefer equations other than

those chosen here as best. In three cases, no single source was outstanding, and a composite equation was derived. In two of the three cases where the ANSI Standard was available, it was found to be the "best" fit.

These "best" equations can be used to describe airblast parameters produced by explosions at long distances. They should only be used over the scaled distance range of 6-200 $m/kg^{1/3}$ (a range in peak pressure from 21 kPa to 440 Pa).

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LONG RANGE (LOW PRESSURE) AIR BLAST PARAMETERS

by

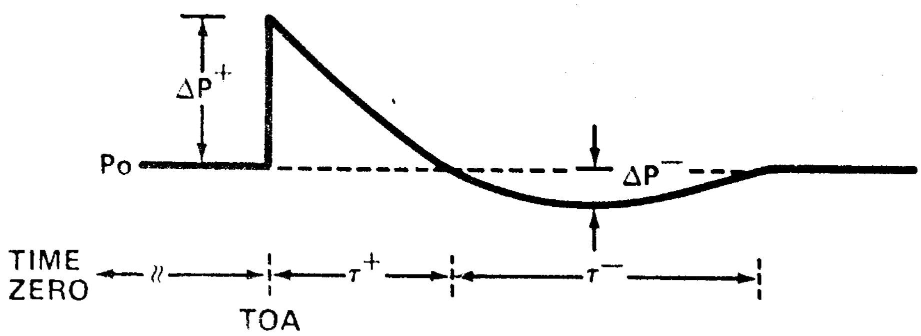
Michael M. Swisdak, JR.

BIBLIOGRAPHIC MATERIAL

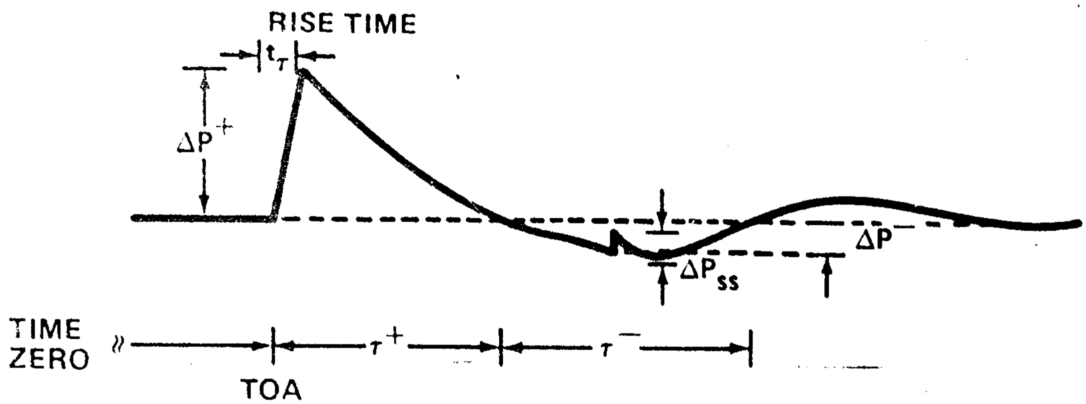
SOURCE	COUNTRY	EXPLOSIVE	COMMENTS	REFERENCE NUMBER
GRANSTROM	SWEDEN	TNT	FREE AIR DATA; QUASI-THEORETICAL	2
POTTER & JARVIS	UNITED KINGDOM	TNT	FREE AIR DATA; EXPERIMENTAL	3
KINGERY	USA	TNT	SURFACE BURST; EXPERIMENTAL	4,11
ANSI	USA	NUCLEAR	FREE AIR; THEORETICAL	5
HE	USA	COMP. B	SURFACE BURST ; EXPERIMENTAL	6
SADWIN & SWISDAK	USA	ANFO	SURFACE BURST ; EXPERIMENTAL	7
NUCLEAR	USA	NUCLEAR	FREE AIR & SURFACE BURSTS ; EXPERIMENTAL	8
SADWIN & CHRISTIAN	USA	RDX/PETN	SURFACE BURST; EXPERIMENTAL	9
UTE	USA	TNT	FREE AIR; THEORETICAL	12

PARAMETER	EQUATION	SOURCE
TIME OF ARRIVAL (ms)	$TOA = 0.9306 W^{1/3} \lambda^{1.4739-0.0490 \ln\lambda}$	COMPOSITE (POTTER & JARVIS AND KINGERY)
PEAK POSITIVE OVERPRESSURE (kPa)	$\Delta p^{+} = 150.2 \lambda^{-1.1}$	ANSI STANDARD
MAXIMUM UNDERPRESSURE (kPa)	$\Delta p^{-} = 46.48 \lambda^{-1.054}$	POTTER & JARVIS
PEAK-TO-PEAK PRESSURE (kPa)	$P_K = 319.807 \lambda^{-1.201}$	COMPOSITE (POTTER & JARVIS & GRANSTROM)
PEAK PRESSURE OF SECOND SHOCK (kPa)	$P_{SS} = 93.67 \lambda^{-1.446}$	POTTER & JARVIS
POSITIVE DURATION (ms)	$\tau^{+} = 1.653 W^{1/3} \lambda^{0.5470-0.0422 \ln\lambda}$	GRANSTROM
POSITIVE IMPULSE (Pa-s)	$I^{+} = 367.125 W^{1/3} \lambda^{-1.0801+0.0072 \ln\lambda}$	ANSI STANDARD
NEGATIVE DURATION (ms)	$\tau^{-} = 18.56 W^{1/3}$	COMPOSITE (HE AND NUCLEAR)
NEGATIVE IMPULSE (Pa-s)	$I^{-} = 240.057 W^{1/3} \lambda^{-0.8252-0.0172 \ln\lambda}$	GRANSTROM

TABLE 2   EQUATIONS FOR LONG RANGE AIRBLAST PARAMETERS



IDEAL BLAST WAVE



"REAL" BLAST WAVE

FIGURE 1 DEFINITIONS OF AIRBLAST PARAMETERS

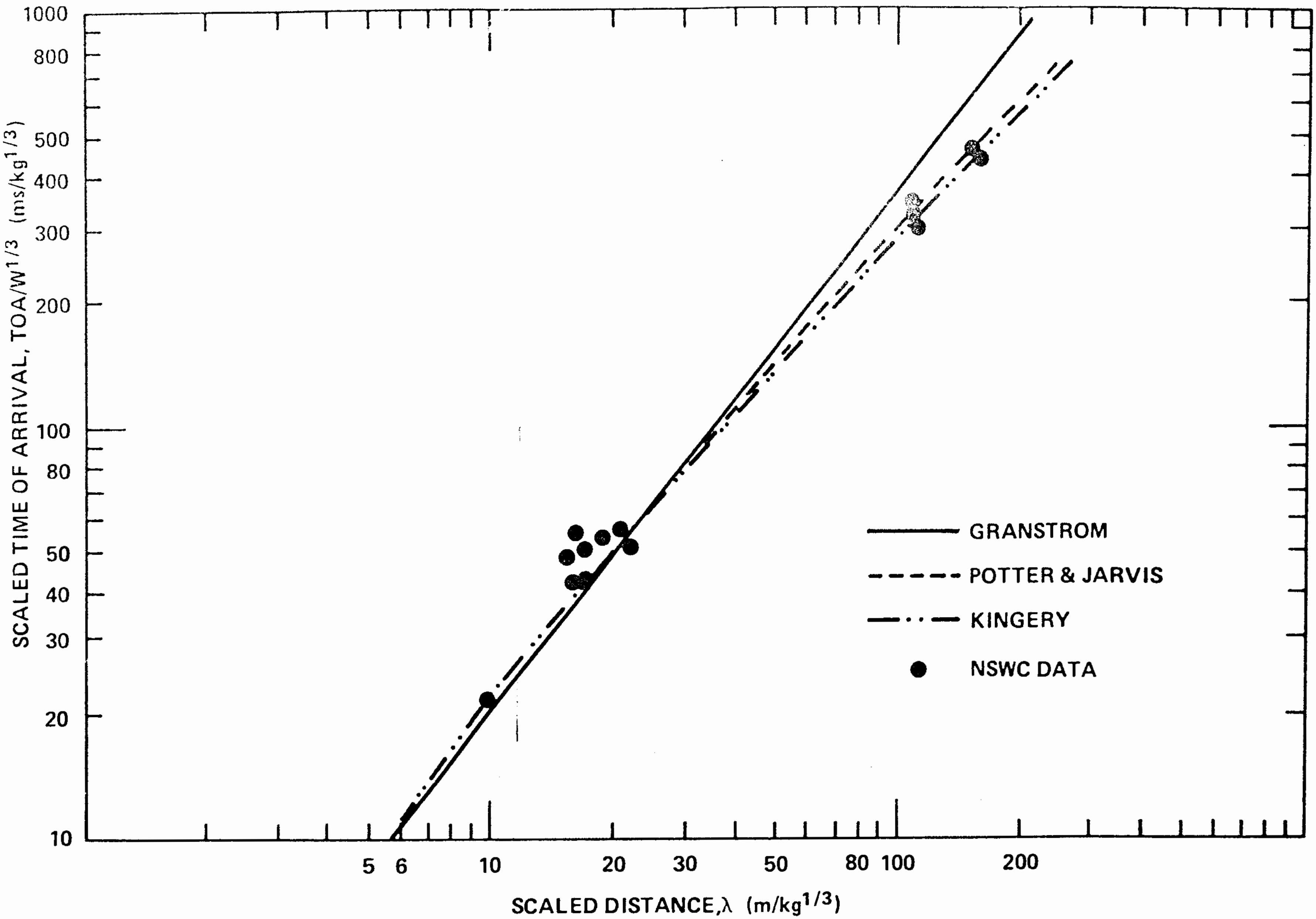


FIGURE 2 SCALED TIME OF ARRIVAL VS. SCALED DISTANCE

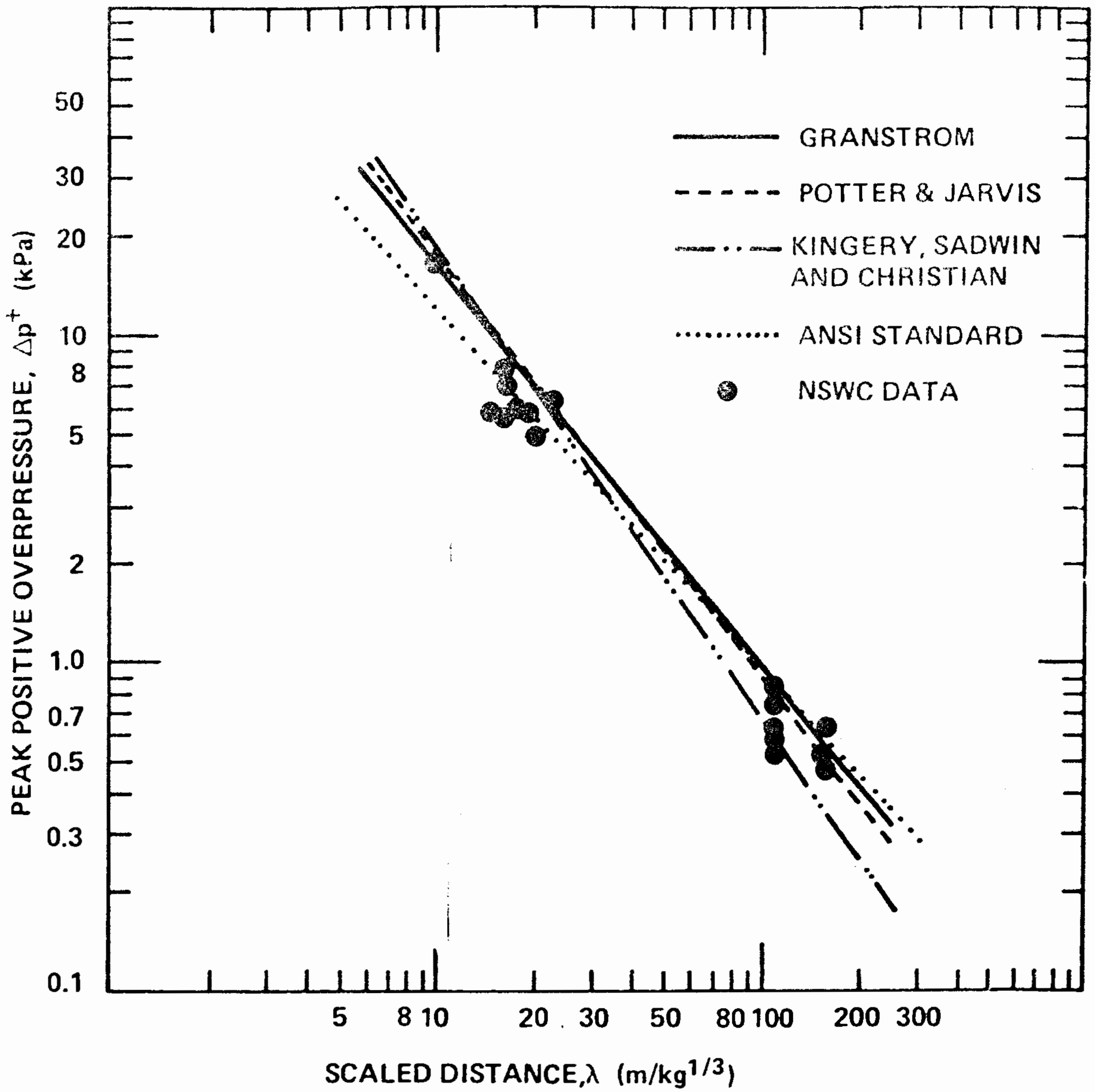


FIGURE 3 PEAK POSITIVE OVERPRESSURE VS. SCALED DISTANCE

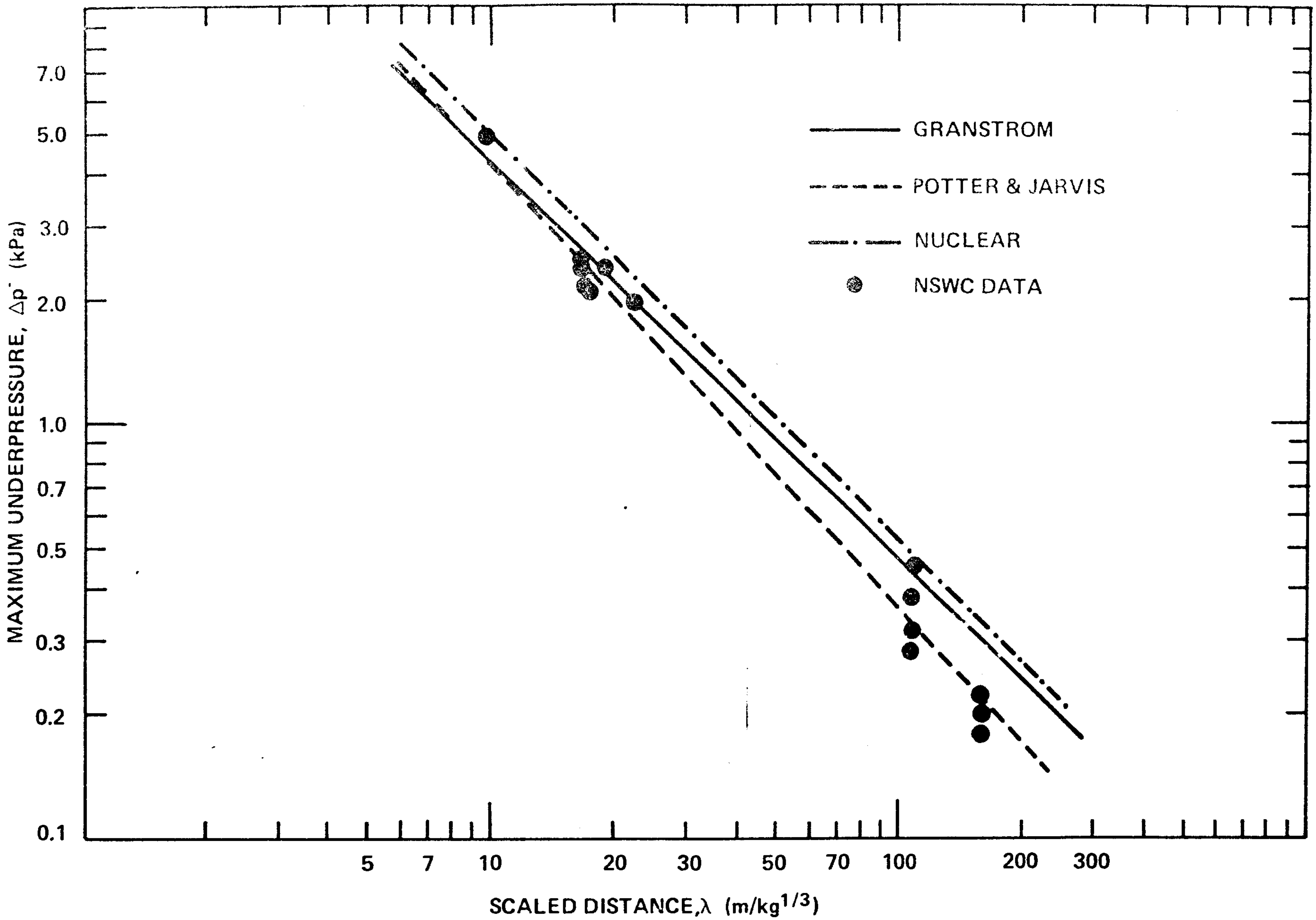


FIGURE 4 MAXIMUM UNDERPRESSURE VS. SCALED DISTANCE

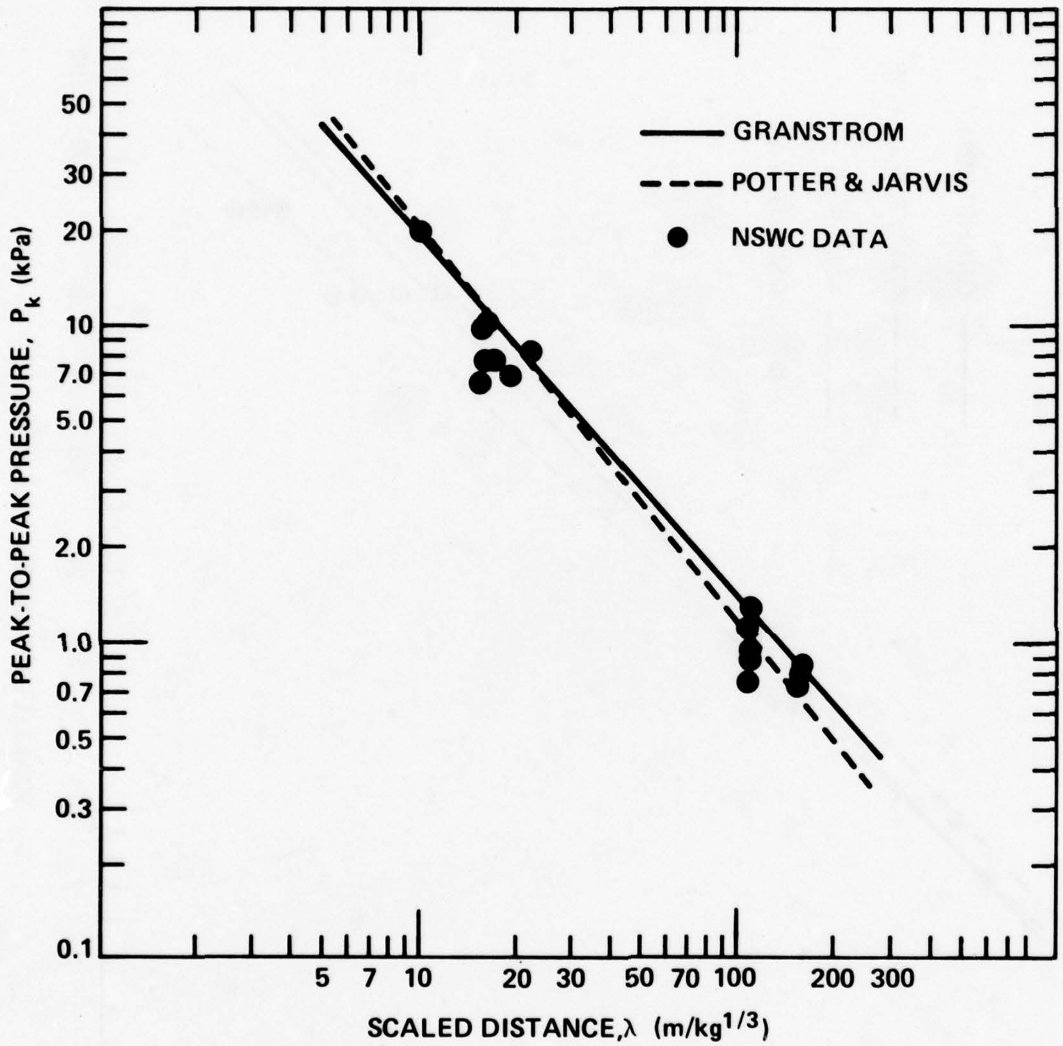


FIGURE 5 PEAK-TO-PEAK PRESSURE VS. SCALED DISTANCE

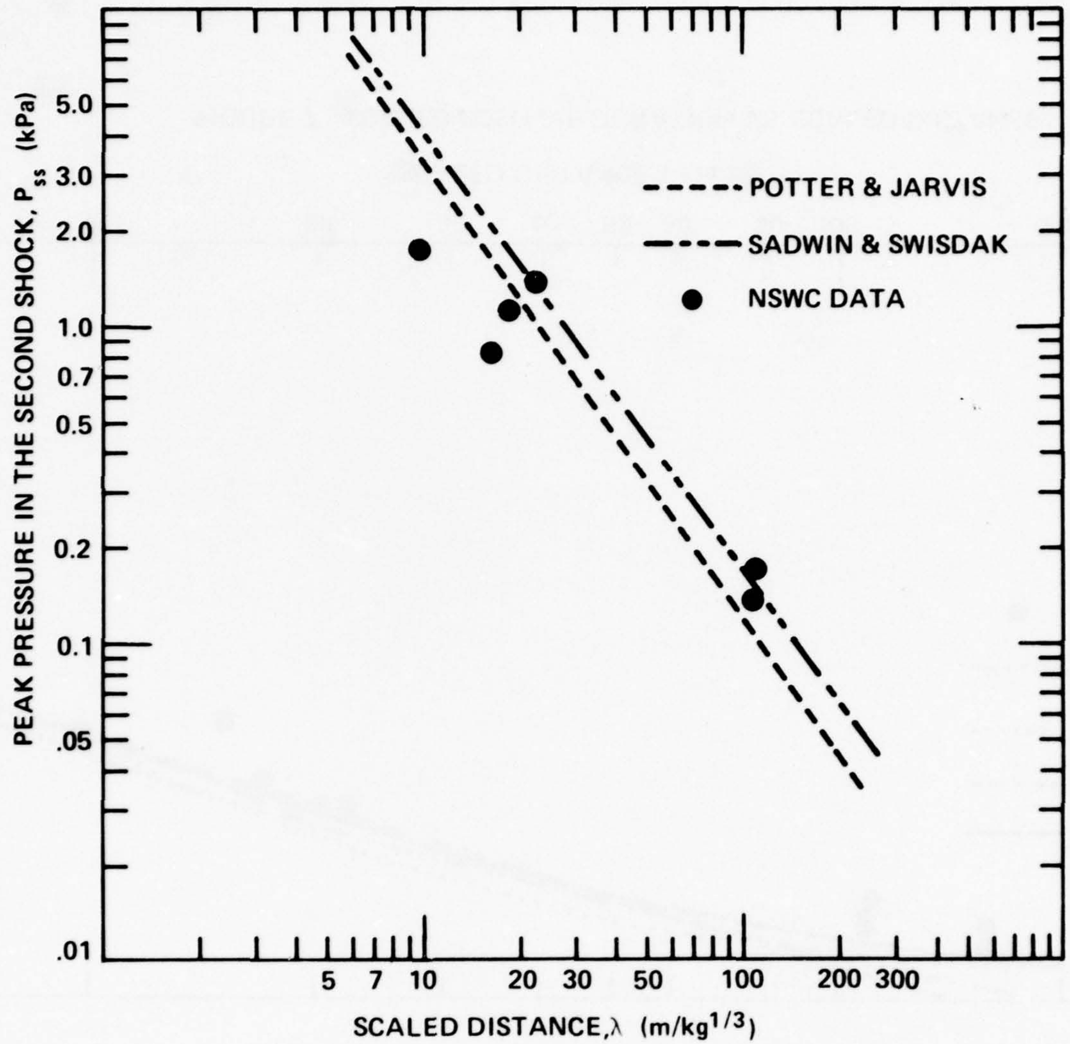


FIGURE 6 PEAK PRESSURE IN THE SECOND SHOCK VS. SCALED DISTANCE

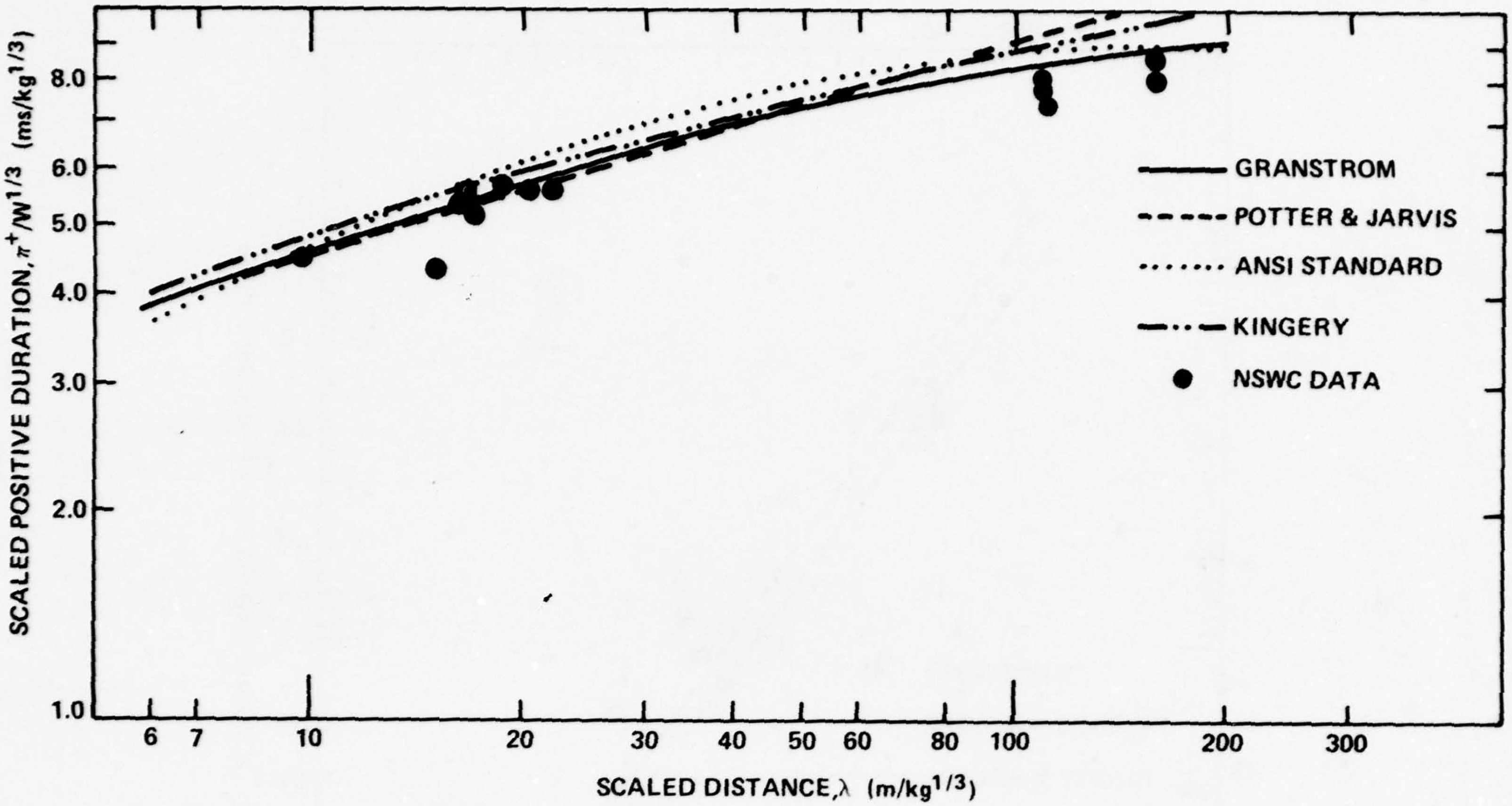


FIGURE 7 SCALED POSITIVE DURATION VS. SCALED DISTANCE

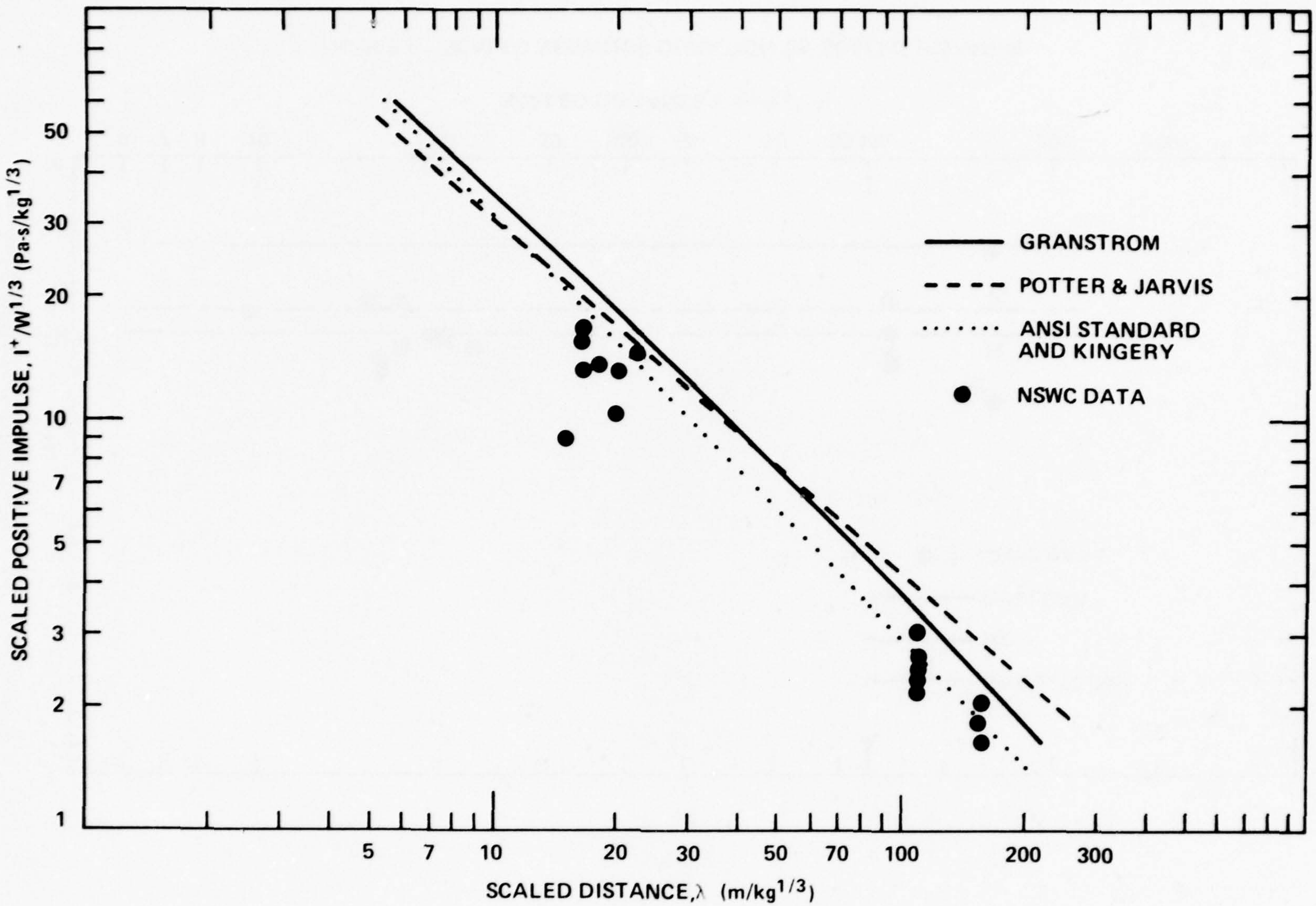


FIGURE 8 SCALED POSITIVE IMPULSE VS. SCALED DISTANCE

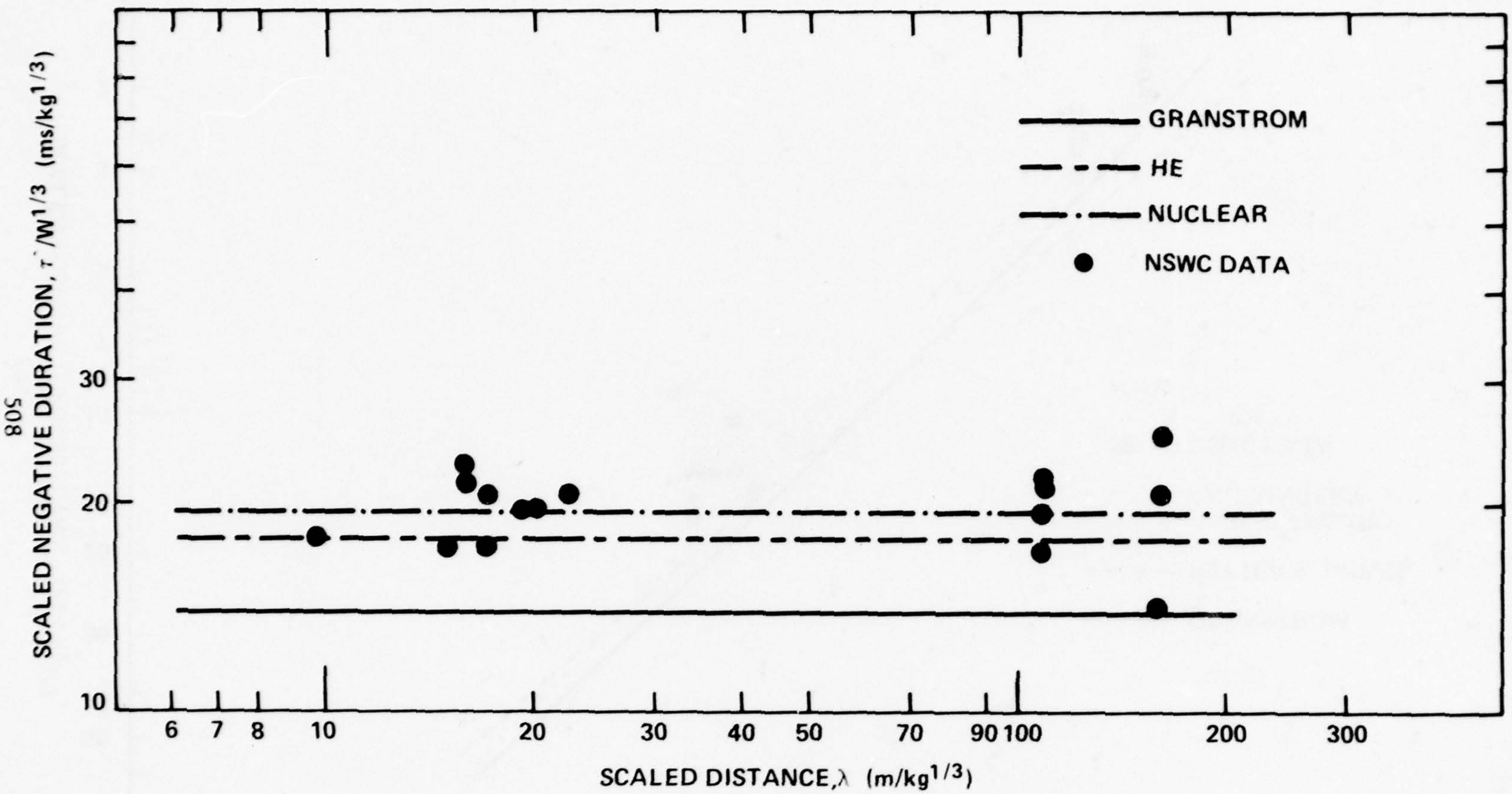


FIGURE 9 SCALED NEGATIVE DURATION VS. SCALED DISTANCE

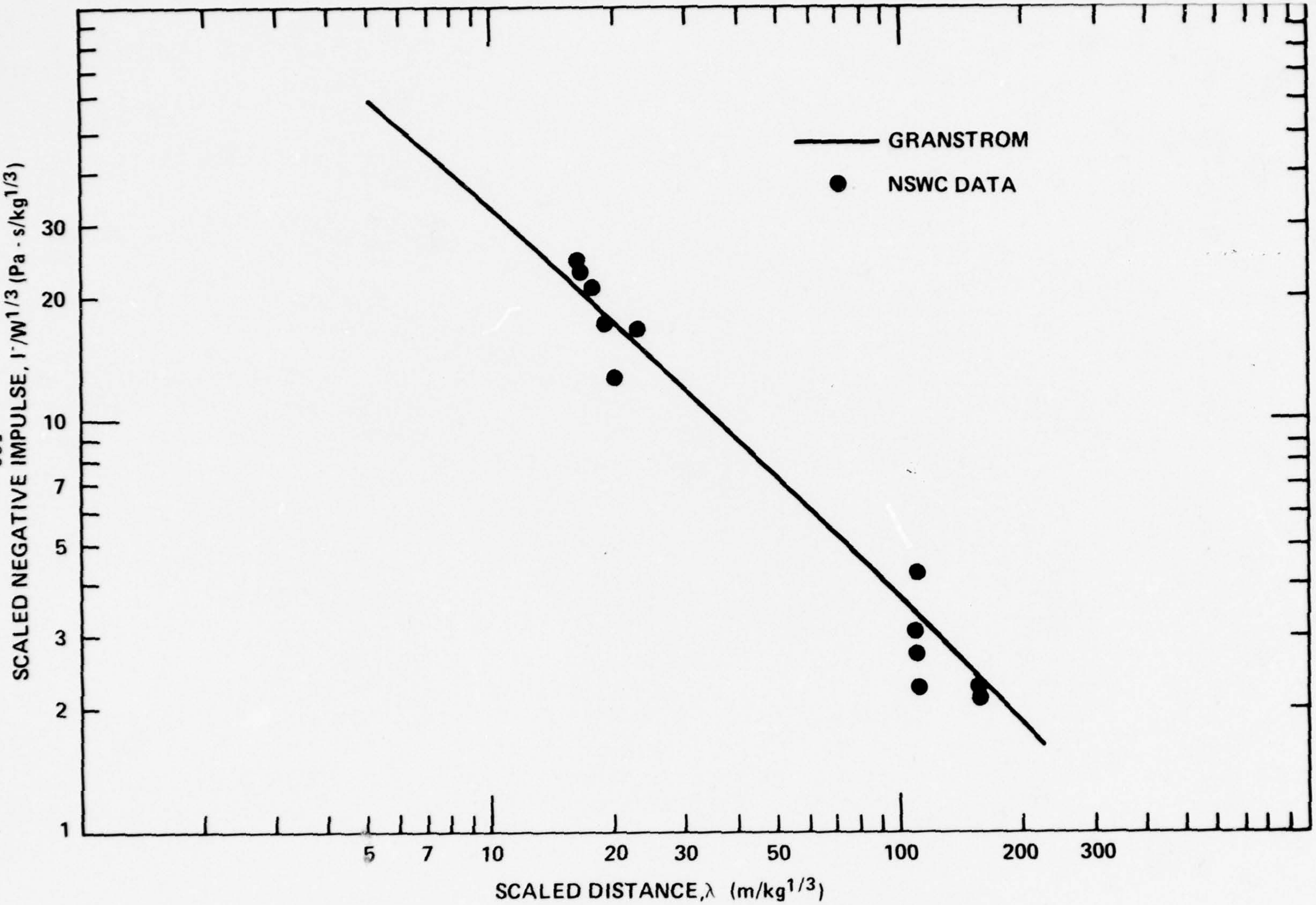


FIGURE 10 SCALED NEGATIVE IMPULSE VS. SCALED DISTANCE

PRACTICAL ASPECTS OF SOIL AS A PROTECTIVE CONSTRUCTION MATERIAL

By: William V. Hill

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PRACTICAL ASPECTS OF SOIL AS A PROTECTIVE CONSTRUCTION MATERIAL

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ABSTRACT

A review of available test data validates that earth cover can be used to attenuate peak overpressures. It also adds mass to a structure to reduce accelerations from blast pressures and stop penetration from fragments. Earth cover over donors attenuates peak overpressures and impulses in the near field. Using the compression ring theory for metal arches, the predominant stresses are compression and soil is a successful building material.

ATTENUATION

A. AIR BLAST

There is a large volume of information available on the attenuation of an air blast from a nuclear explosion through earth cover. For partially buried or mounded structures having shallow earth covers, the attenuation of the peak overpressure caused by a nuclear explosion is zero for design purposes. A literary search on the attenuation of the overpressure caused by an HE explosion through earth turned up very little information. Reviewing the results from tests that have been performed in the past, at the Naval Weapons Center at China Lake, the data have been tabulated and are shown on Figure 1. Although the test data are very limited, they

ATTENUATION OF PEAK PRESSURE IN EARTH

PEAK PRESSURE P.S.I.	EARTH COVER FT.	MAX. PRESSURE P.S.I.	ATTENUATION %
25	3	2 VERTICAL	92
25	3	2 HORIZONTAL	92
54	8	11 VERTICAL	80
54	8	12 HORIZONTAL	78
100	8	15 VERTICAL	85
100	8	9 HORIZONTAL	91
100+	5	20 VERTICAL	80+
100+	5	20 HORIZONTAL	80+

FIGURE I

show a high percentage of attenuation of the air blast. It is assumed that the attenuation is because of the very short duration of the overpressure from an HE explosion which is in the milliseconds. When the peak overpressure of a nuclear explosion is of the same magnitude as that for an HE explosion, the duration is for several seconds for the nuclear explosion depending on the weapon size. For design purposes, there is not enough data available to develop any equations for the attenuation of the peak overpressure through earth cover caused by an HE explosion.

After the Naval Weapons Center test of the horizontal-spanning single-leaf sliding door, it was possible using the impulse curve to calculate the deflection of the door to within 10 percent of the actual deflection. The crown of the oval steel arch magazine did not have the large downward permanent deflections as predicted, both with the concrete thrust beams and without them. This was probably because of the large attenuation of the overpressure through the earth cover and the top of the steel arch did not receive the loading that was predicted. Attenuation of the air blast depends on the shape of the impulse curve at the earth's surface, the depth of the earth cover, and the soils property, whether it is of the silty clay classification or of the sandy gravel classification, the density, due to compaction, and the moisture content.

B. GROUND SHOCK

Ground motions associated with high-explosive detonations are induced by two distinct processes; air-induced ground shock and direct-transmitted

ground shock. The air-induced shock is caused by the blast wave traveling over the ground surface and generating stress waves into the ground which creates ground motions. Unless the structure is buried, the overpressure or impulse will control the design.

The Bureau of Mines of the Department of Interior has compiled a large quantity of data on the effect of direct-transmitted ground shock caused by blasting. This information can be found in Bulletin 656 entitled "Blasting Vibrations and Their Effect on Structures". The attenuation depends on the size of the charge and whether there are layers of various type materials.

From TM 5-855-1, "Fundamentals of Protective Design (Non-Nuclear)", the formula for the horizontal displacement caused by direct-transmitted ground shock, is $D = \dfrac{1.3W^{4/3}}{r^3}$ where

D = permanent horizontal displacement measured in feet.

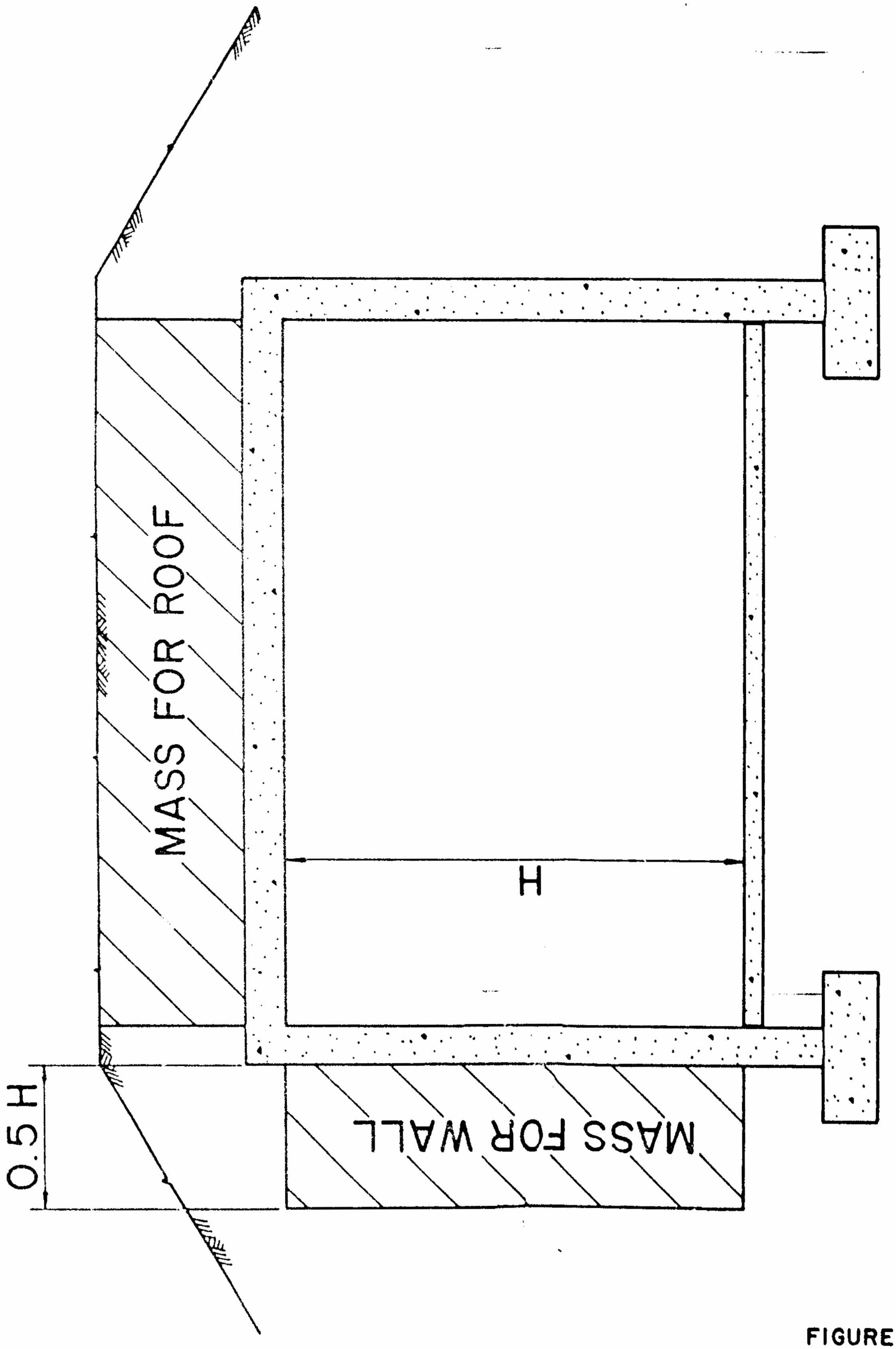
W = weight of charge in pounds.

r = horizontal distance from point of explosion in feet.

The above formula was derived from tests conducted in a soil consisting of clay silt and sand in local deposits without continuous stratification.

MASS

Soil can be used to add mass to structural elements (see Figure 2). From Newton's second law, which may be put in either of two equivalent forms,



MASS OF EARTH TO BE USED
FOR DESIGN OF STRUCTURE ELEMENTS

FIGURE 2

force is proportional to the product of mass and acceleration: $F = ma$ or force is proportional to rate of change of momentum: $F = \frac{mv}{t}$. This form of Newton's second law may be written: $Ft = mv$ where the quantity Ft is the impulse. For elements which respond to the impulse, the maximum response depends upon the area under the pressure-time curve. The magnitude and time variation of the overpressure are not important. From TM 5-1300, "Structures to Resist the Effects of Accidental Explosions", elements which are impulse load sensitivity and deflection is limited to partial failure, the equation is: $\frac{ib^2}{2\ mu} = ru\ Xm$. This may be written $Xm = \frac{ib^2}{2\ mu\ ru}$ where:

Xm = maximum deflection

ib = unit blast impulse

mu = effective unit mass in the ultimate range

ru = ultimate unit resistance

The effective mass, in the ultimate range $mu = 0.66\ m$, where m is the unit mass, it can be seen that the maximum deflection can be limited to the allowable by increasing the effective mass, the ultimate resistance of the structure element, or both.

For elements which respond to pressure-time relationship, the pressure and duration of the applied blast loads must be known. The determination of the dynamic response of these elements is accomplished using a response chart, from TM 5-1300, which relates the dynamic properties of the blast loads (pressure and duration) to those of the element

(natural period of vibration, resistance and deflection). By the use of earth cover, the natural period of vibration may be varied. The effective natural period of vibration is

$$TN = 2\pi\sqrt{\frac{KLM\ m}{KE}}$$

where:

KLM = load-mass factor

m = unit mass

KE = equivalent elastic unit stiffness

By adding additional earth cover, the mass of the element will be increased which increases the effective natural period of vibration. This reduces the ratio of the time of the load duration to the natural period of vibration $\left(\frac{T}{TN}\right)$. With a lower value of $\left(\frac{T}{TN}\right)$ less ultimate resistance of the element is required to maintain the same ductility factor.

Earth cover may also be used for HE storage structures requiring partial containment of blast or complete structural fragment containment (see Figure 3). Not only does the earth load on the roof add mass, but also increases the resistance of the roof and side walls.

The addition of earth cover also has its disadvantages and the point of diminishing returns will be reached. Besides the cost of placing the earth cover, higher portals and wing walls are required with larger footings. The additional dead load on the structure must be considered both in static and dynamic design. The designer must find the depths of

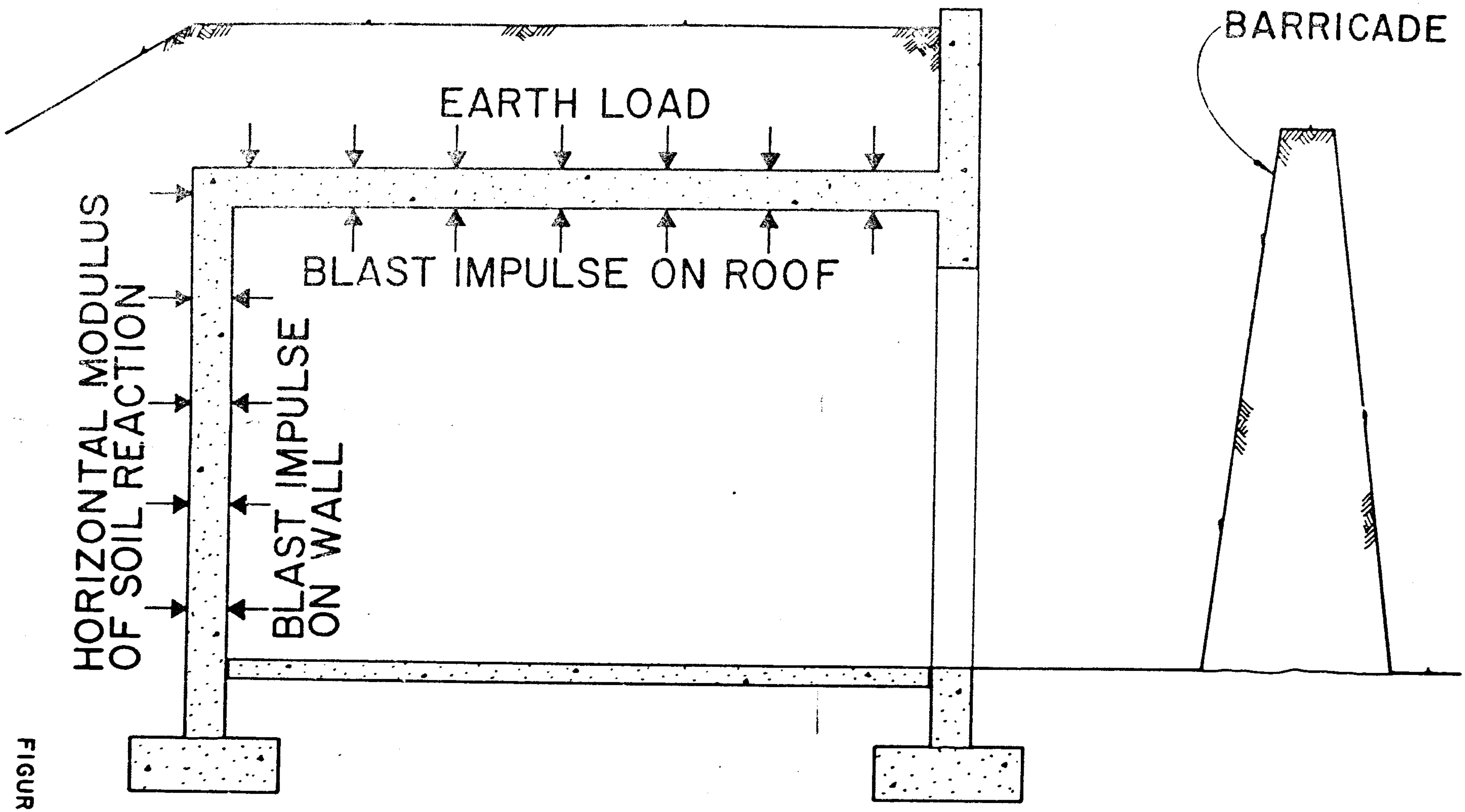


FIGURE 3

EARTH TO RESIST INTERNAL BLAST PRESSURES

earth cover which give the most economical design.

BLAST PRESSURE REDUCED BY EARTH COVER OVER DONOR

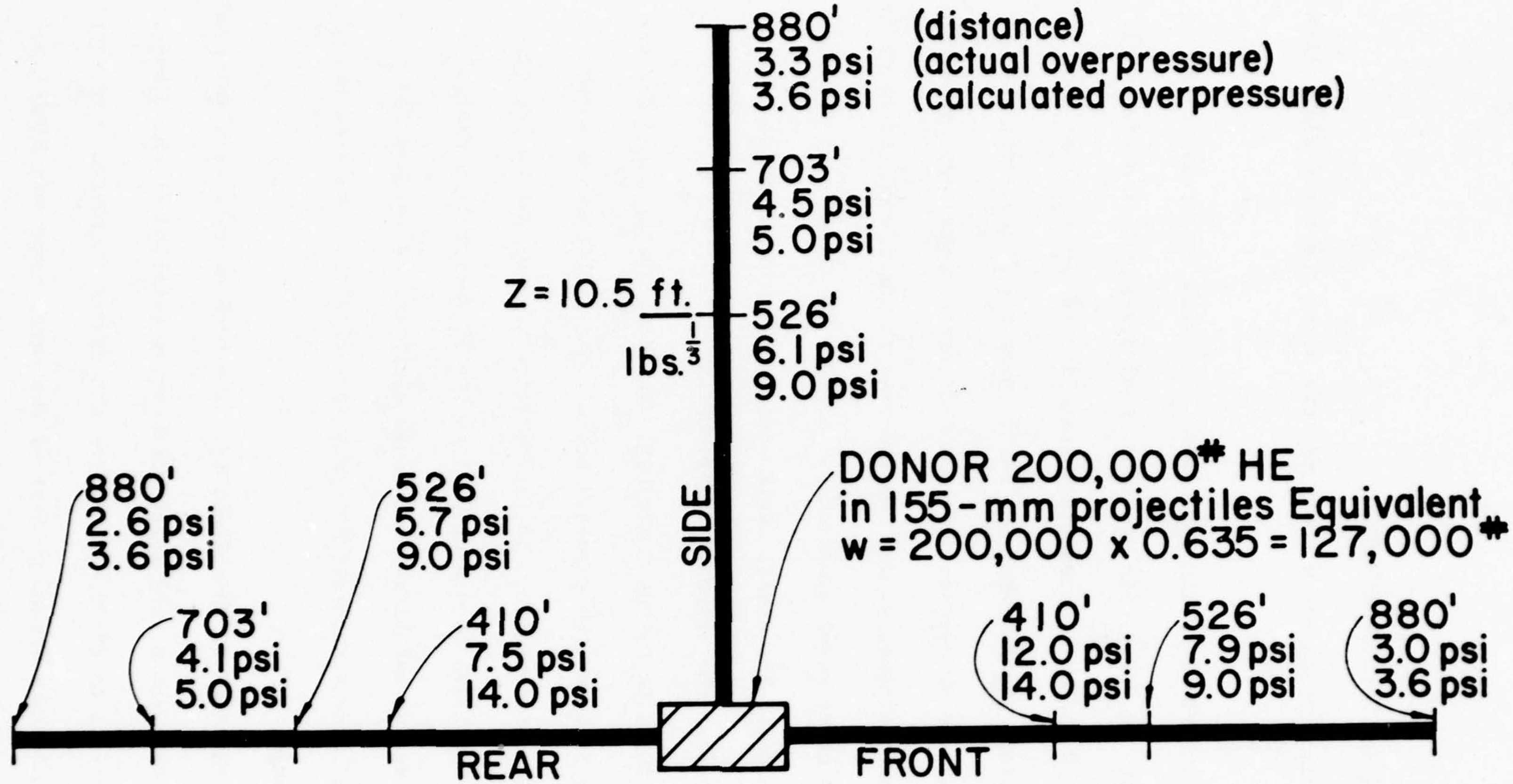
The series of tests that have been performed using earth covered steel arch magazines loaded with high explosives as donors has shown that there has been a large reduction in blast pressures compared to explosives stacked in the open. From the Eskimo I test, the overpressures to the front side and rear of the donor for various distances are shown on Figure 4. The donor contained 200,000 pounds of HE in 155-mm projectiles. Using a factor of 0.635 for the energy expended in breaking up the metal cases, we have an equivalent weight of 127,000 pounds. Calculated overpressure was obtained from the standard curve for hemispherical TNT surface explosion at sea level. The largest reductions are close in when the scaled distance is less than 10 ft/lbs 1/3, with the front location having the least reductions and the rear location the largest. The results are consistent with other tests.

A. OBJECTIVES OF SCALE MODEL TESTS

From BRL Memorandum Report No. 2680, "Blast Parameters from explosions in Model Earth Covered Magazines", September 1976, primary objectives of the proposed two of the 1/50 scale model tests were as follows:

1. DETERMINE THE BLAST PARAMETERS propagating along blast lines extending to the front, side, and rear of a magazine with a standard earth cover.

2. DETERMINE THE EFFECT ON BLAST PARAMETERS when the earth cover was varied from no cover, to one-half the standard cover, and to double the



COMPARISON OF
OVERPRESSURES WITH DISTANCE
FOR UNCONFINED TNT

FIGURE 4

standard cover.

B. CONCLUSIONS ON EARTH COVER EFFECTS

Some specific conclusions on earth cover effects along the three blast lines are as follows:

1. BLAST LINE TO THE FRONT OF THE STRUCTURE. The peak overpressure and impulse recorded at the first five stations, scaled separation distance of 2 $ft/lb^{1/3}$ out to 9 $ft/lb^{1/3}$ along the blast line to the front of the structure, were always greater when the earth cover was placed over the charge than when it was uncovered. The one-half earth cover model produced an increase in peak overpressure and impulse over the uncovered charge while the standard earth cover model produced an increase in values over the one-half earth cover model. The double earth cover model did not produce an increase in values over the standard cover model.

2. BLAST LINE TO THE SIDE OF THE STRUCTURE. The peak overpressure for the three earth covers followed the expected trend, that is, the more earth cover the more blast attenuation. The attenuation became less as the distance increased. The impulses measured along the 90 degree line charge showed the same trend as established for peak overpressure in that the three earth covered models recorded impulses less than the uncovered charge in the close-in range.

3. BLAST LINE TO THE REAR OF THE STRUCTURE. The peak overpressure followed the same trend. There was a very large attenuation observed at the close-in range, becoming less as the distance from the charge increased. The attenuation of peak overpressure became greater as the earth cover was increased. The

overpressure impulse recorded along the 180 degree line was greatly attenuated at the close-in stations when the charges were covered. As noted with the peak overpressure, this attenuation became less with increasing distance. For innermagazine sighting purposes, DOD Standard 5154.4S "Ammunition and Explosives Standards" takes into account whether the magazines are earth covered or not.

PENETRATION OF FRAGMENTS

Fragments from an explosion of a munition storage magazine are caused from the construction material of the donor magazine and from the shells, bombs, and other munitions having steel cases which cause a large number of high velocity fragments. An explosion in an ammunition plant can throw large pieces of equipment, pipe, steel members, and concrete for hundreds of feet. The same is true for an aboveground magazine.

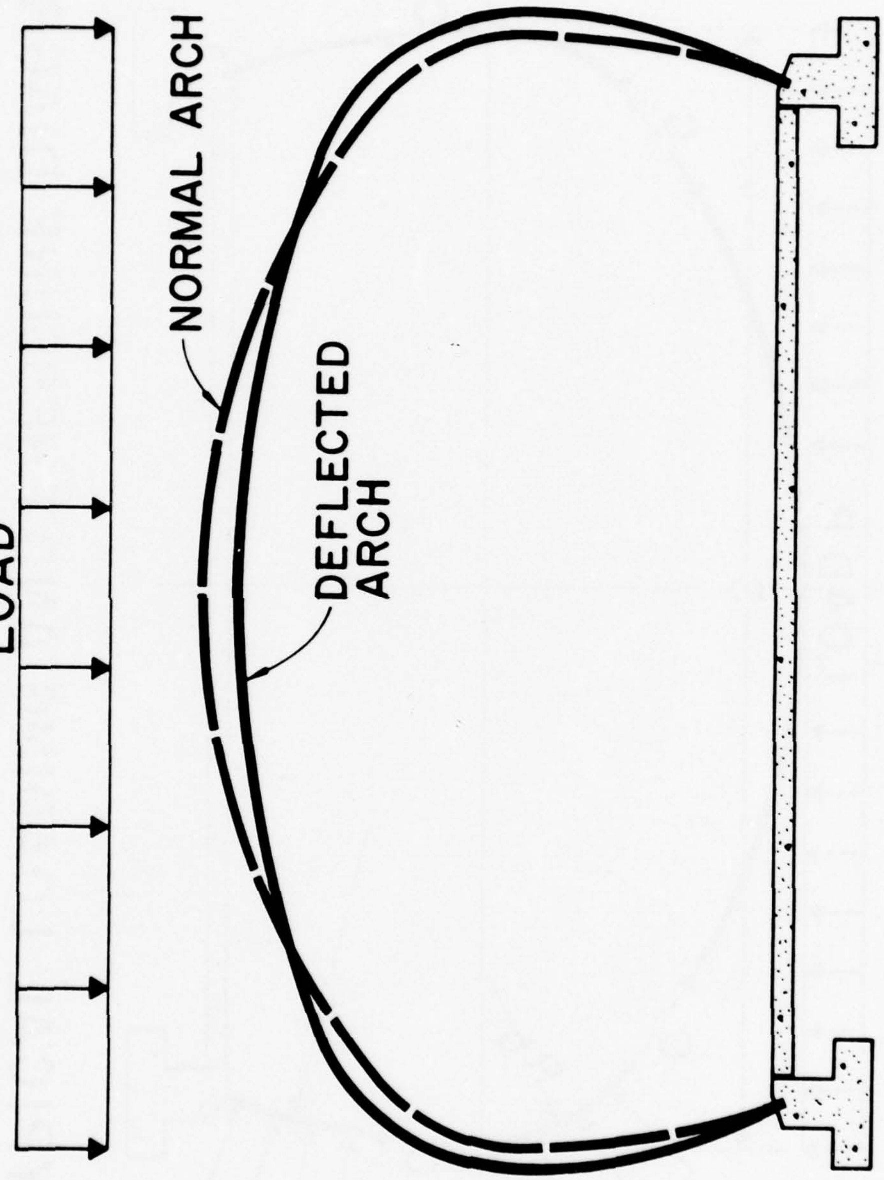
Properly constructed barricades of earth are effective means for protecting ammunition and explosives, structures, or operations against high velocity, low angle fragments, although the barricades may be destroyed in the process. Since such fragments move along ballistic trajectories rather than straight lines, reasonable margins in barricade height and length must be provided. Barricades also provide limited protection against blast in the immediate vicinity, although they do not provide any protection against high angle fragments and are ineffective in reducing the blast pressure in the far field. By analysis of ballistic trajectories, it can be shown that high angle fragments from an explosion strike the

ground surface at approximately their terminal velocity in free fall. The terminal velocity of fragments is much slower than their initial velocity and the penetration into earth is very small.

DOD Standard 5154.4S "Ammunition and Explosive Standards", under quantity distances takes into consideration fragments for inhabited building distances, public traffic route distances, and air field distances both barricaded and unbarricaded. The Standard also gives the minimum requirements for barricades.

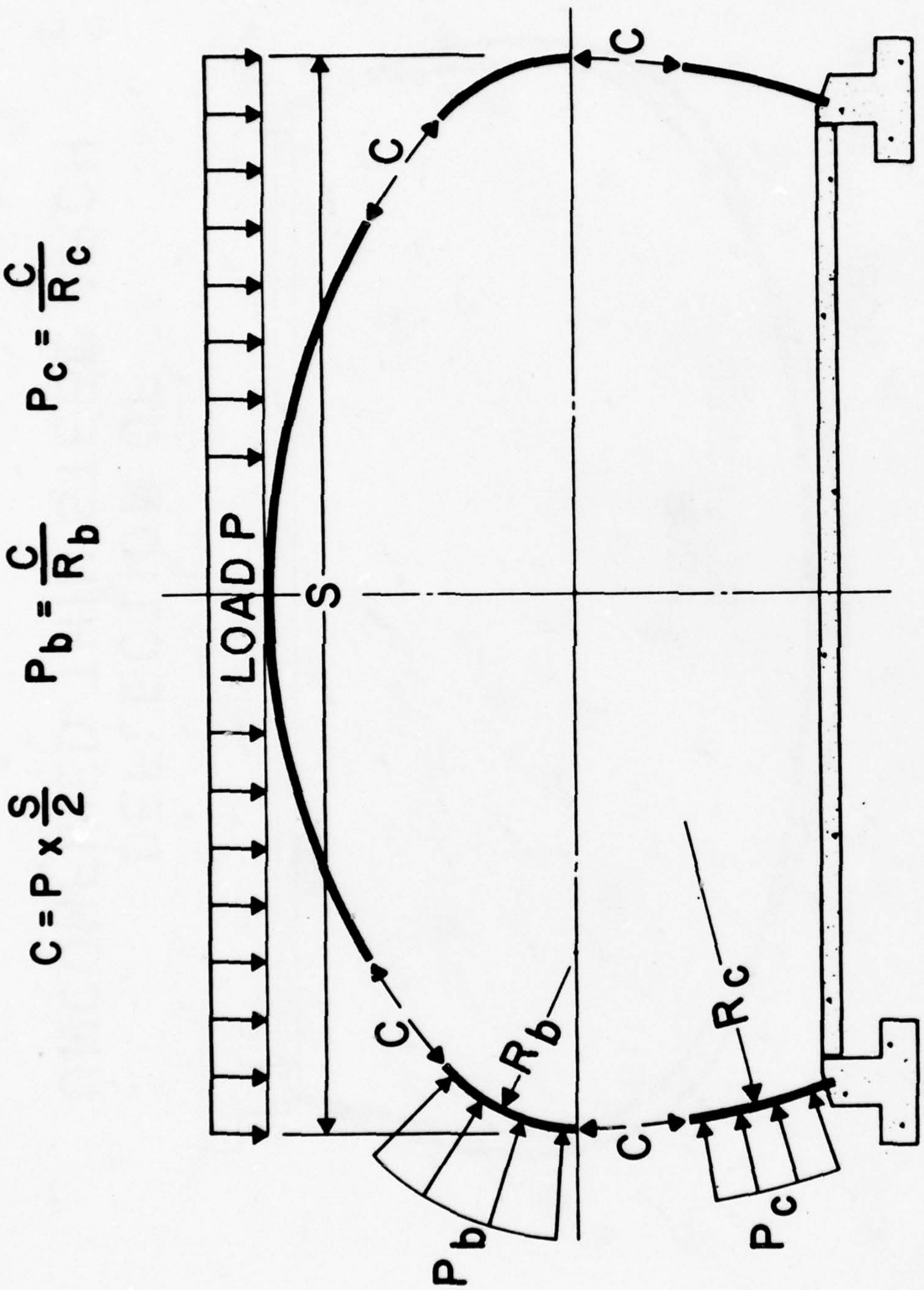
FLEXIBLE STEEL ARCHES AS A COMPRESSION RING

The normal corrugated metal arch or conduit is designed to have sufficient moment strength to permit handling and installation without being unduly flexible. Figure 5 shows the deflection of an unconfined steel arch under vertical loads. Because of its small section modules, its ability to carry additional loads by moments is nil. Once it has been installed in a compacted backfill capable of taking reaction pressures, its strength can then be determined as a thin ring in compression (See Figure 6). From the "Handbook of Drainage and Highway Construction Products", the required wall area and radius of gyration of the arch can be computed to carry the thrust "C" without buckling. The joints in the plates must also be checked for the required number of bolts. The pressure distribution Pb and Pc provides the engineer with data from which to determine what type of soil will be needed around the various shape structures to insure support without undue deformation. The arch configuration is such that the magnitude of



DEFLECTION OF
UNCONFINED THIN STEEL ARCH

FIGURE 5



TYPICAL LOADING AND PRESSURE DIAGRAM
FOR A STEEL ARCH STRUCTURE

FIGURE 6

deflection in the arch is greatly influenced by the stabilizing effect of the surrounding earth fill. At corners where the radius Rb is small compared to the load and the span, the pressure Pb against the earth backfill will be very large. The type and placing of the backfill is very critical for structures designed as thin rings in compression.

On one of our jobs, for a major Military installation, a corrugated metal conduit was used as a connecting tunnel under an earth fill. The specifications required that the fill around the corrugated metal conduit be compacted to at least 95 percent CE-55 maximum density. Shortly after completion of the construction, the tunnel began to collapse. An investigation revealed that the backfill contained large voids. Some of the voids were large enough that it was possible to place your arm in them. Where earth is used as a construction material, it must be installed properly, just as any other material used on the job.

On arches with large spans, the value of the horizontal modulus of soil reaction may be too low to stabilize the arch, the designer may use one of several methods. Republic Steel Corporation's Maxi-Span sectional plate arch uses corrugated compaction wing plates bolted back-to-back and to the structure (See Figure 7). Armco Steel Corporation's Super-Span multiplate steel arch uses concrete thrust beams (See Figure 8). These triangular elements are locked to the corrugated plates by means of hook bolts attached to the plates and cast into the concrete. The thrust beam transfers the thrust in the top arch into the well-compacted soil against

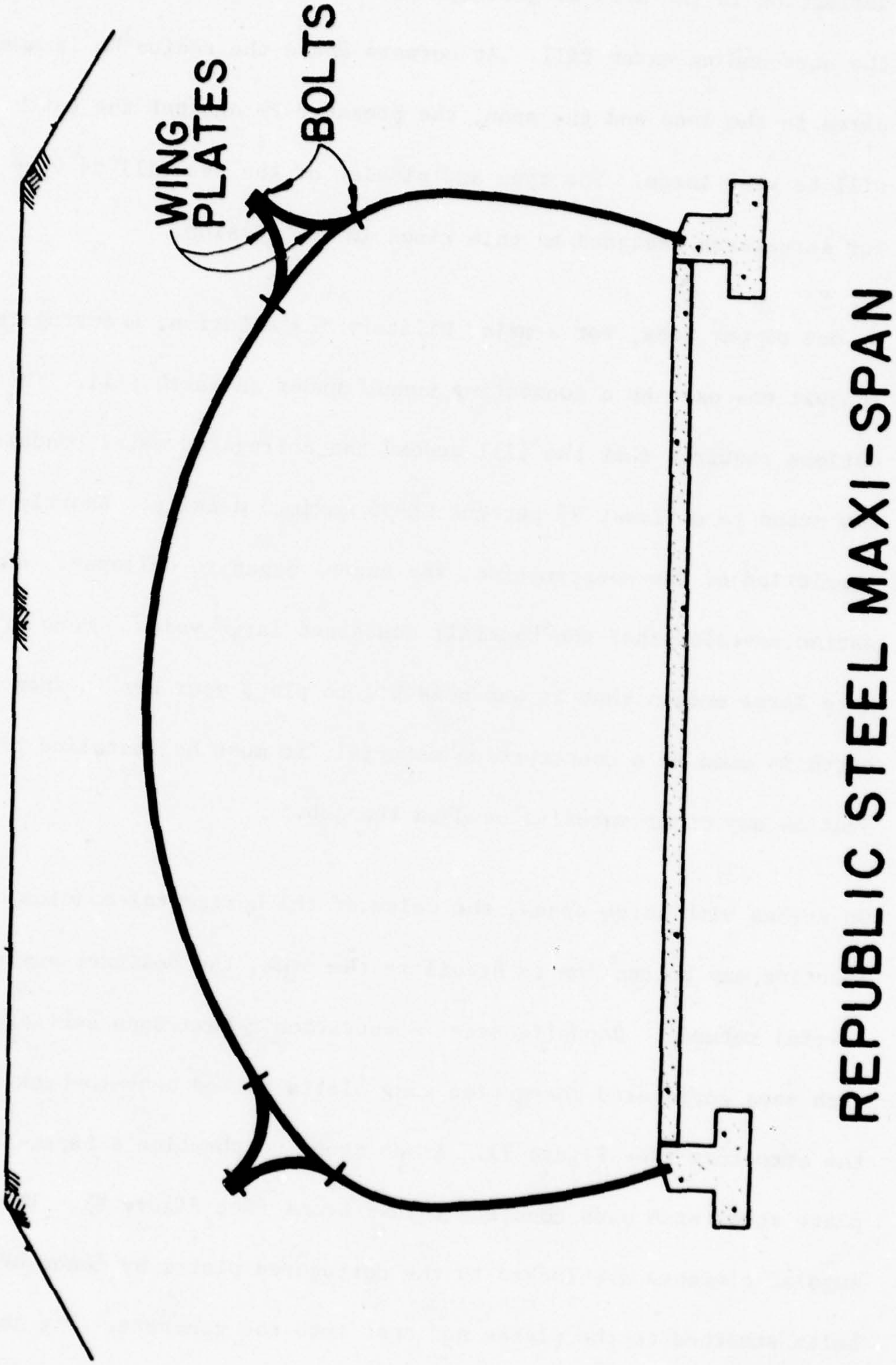
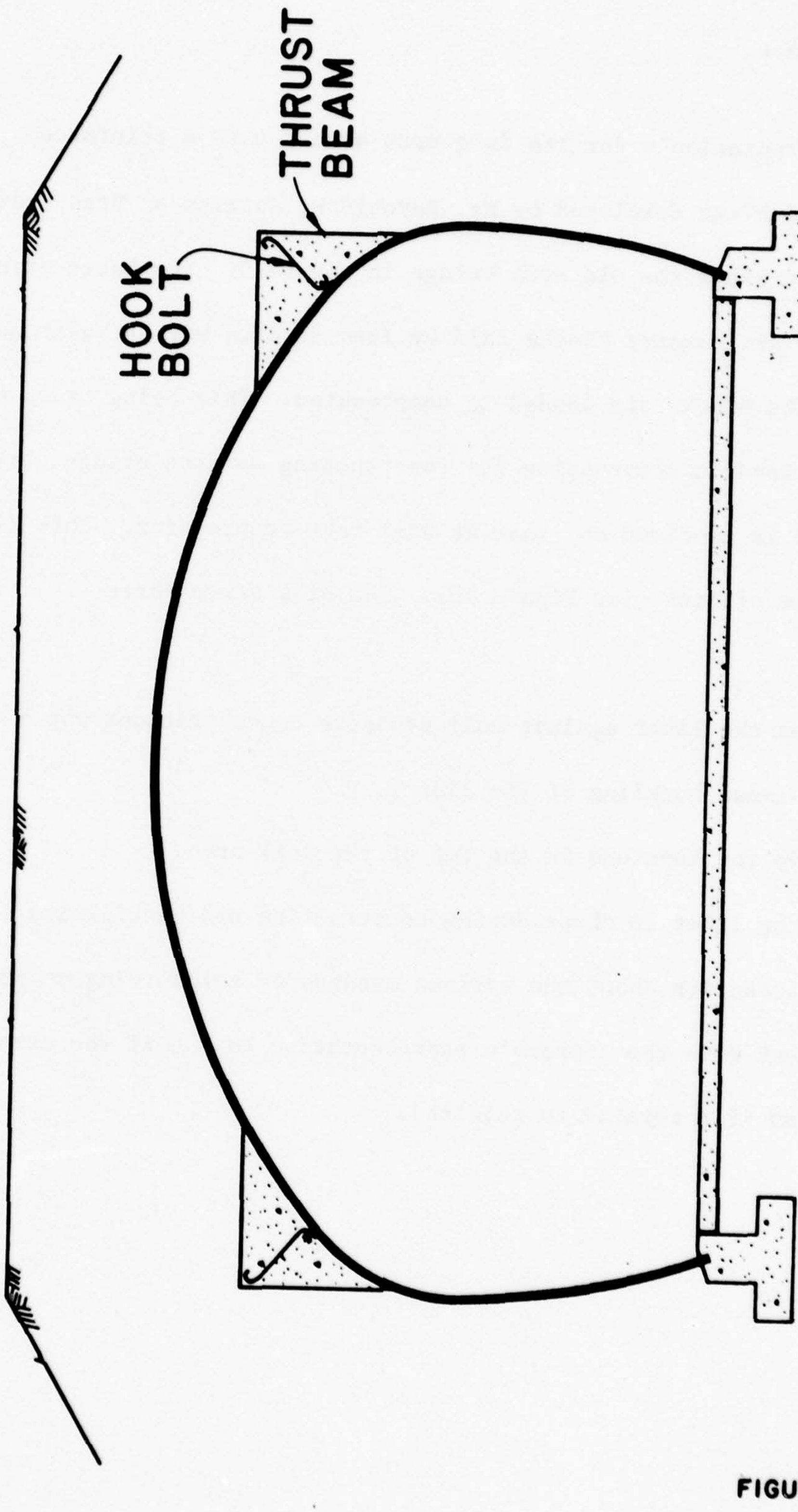


FIGURE 7



ARMCO STEEL SUPER-SPAN

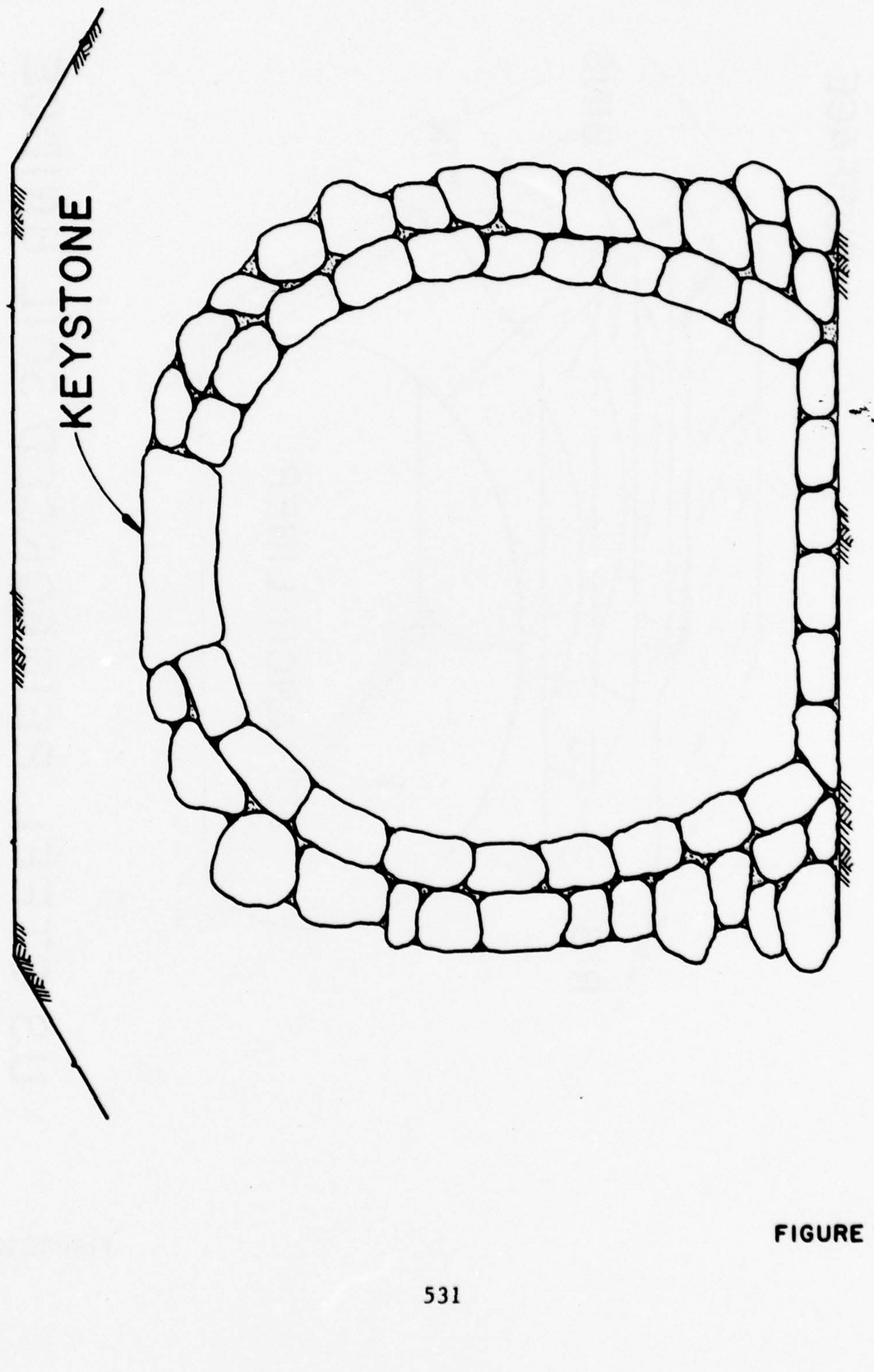
FIGURE 8

its vertical face.

U. S. Steel Corporation's for its long span arches uses a reinforced soil bridge which was developed by Mr. Reynold K. Watkins of Utah State University. Consider the old arch bridge in Figure 9. The basic structural elements are masonry blocks laid up into an arch with a keystone at the top. The blocks are loaded in compression. This being true, soil could also be used in compression for constructing an arch bridge, provided the soil is confined so that it will take compression. This is done by the use of bins (See Figure 10). The bins serve three purposes.

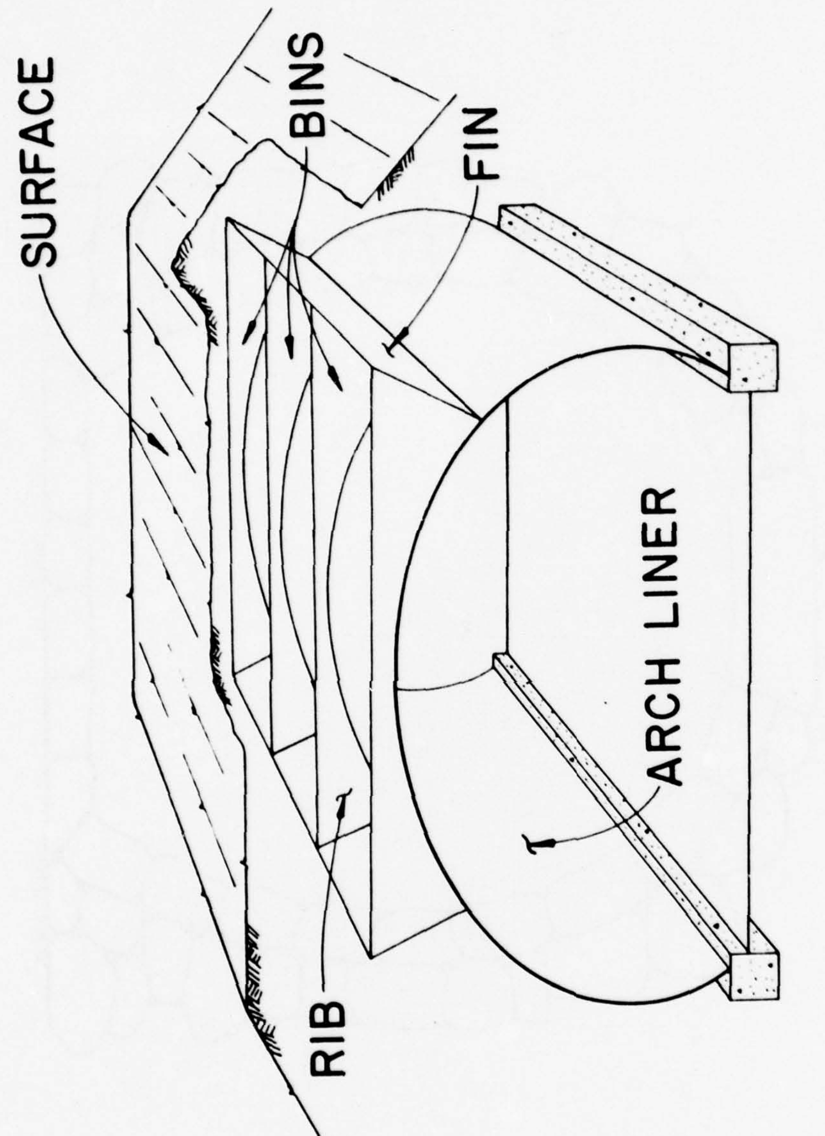
- Stiffen the liner against soil pressure concentrations which could cause buckling of the liner.
- Develop the keystone in the top of the soil arch.
- Hold the liner in shape during construction and backfilling.

Just a word of caution about the various methods of reinforcing an arch. You should check with the company's representative to see if the method is patented and if a royalty is required.



BURIED MASONRY ARCH

FIGURE 9



U.S. STEEL REINFORCED SOIL BRIDGE

FIGURE 10

BLAST CAPACITY EVALUATION OF BELOWGROUND STRUCTURES AND SINGLE REVETTED BARRICADES

BY

JOSEPH P. CALTAGIRONE, US ARRADCOM
PAUL D. PRICE, US ARRADCOM
SAMUEL WEISSMAN, AMMANN & WHITNEY

ABSTRACT

A series of explosion tests was performed to evaluate the capacity of reinforced concrete below ground and single revetted structures to resist the effects of explosive loadings. These structures were designed as standard earth retaining walls and did not contain the "lacing" utilized in blast resistant wall design. In both situations the earth backing substantially increased the blast capacity of the structure. Information is provided concerning the maximum charge weights each structure can safely withstand.

INTRODUCTION

Modern day explosive manufacturing and loading plants require special construction to achieve safe operating systems. With the use of belowground reinforced concrete structures and single-revetted barracades, "barricaded intraline distance" may be utilized for siting and result in cost savings for utilities and other facilities connecting various buildings. However, there is no quantitative method to determine the maximum quantity of explosive which may be used with these structures. They are designed for conventional loads, i.e., as earth retaining walls. This allowable charge capacity is of significant importance particularly when the structure is close to a potential explosion.

In order to obtain data relative to the performance, capacity, and damage to belowground structures and single-revetted barricades, two series of tests were conducted at Dugway Proving Ground under the direction of the US Army Armament Research & Development Command and with the assistance of Ammann & Whitney. This paper briefly summarizes the results of these tests in two sections.

SINGLE-REVETTED BARRICADE

TEST STRUCTURES

Two structures were built for the purpose of this test program. Each consisted of a reinforced concrete wall and earth mound, designed simply as a retaining wall without additional reinforcement to resist the blast loadings. The size of each test structure was representative of a one-third scale model as shown in Figure 1. Each wall was 2.44m (8ft) high by 4.88m (16ft) long and 0.25m (10in) thick. Support was provided by a 1.78m (5ft-10in) long reinforced concrete slab (0.31m (1ft) thick) which was cast monolithically with the wall. Both the wall and slab were reinforced with No.3 bars positioned 0.2m (8in) on center in both directions. To simulate the concrete floor slab of an adjoining building a 0.15m (6in) thick concrete slab was poured adjacent to the foundation slab. This produced the reflections of the blast wave which could be expected to be associated with an explosion in a building immediately adjacent to a barricade.

Located to the rear of each wall was an earth-mound, conforming to the requirements of AMCR 385-100 (Ref 4), with a height equal to the height of the wall. The mound was even with the wall for a distance of 0.91m (3ft) then tapered to the ground on a 2 to 1 slope. The 0.91m dimension of the mound was selected based upon the criterion developed for this project which recommends that the width of the full height section of mound should be at least equal to one-third of the wall height. The soil throughout the mound was compacted to 92 percent of the maximum dry density.

INSTRUMENTATION

Only Wall No. 1 was equipped with six electronic deflection gages, five in the wall and one in the slab. The deflection rods were connected to steel rods which passed through pipe sleeves to prevent binding by compacted earth (Fig 2). Hand measurements were made to verify the results obtained electronically. A streak camera was also used to determine wall displacement. One light was attached to a deflection rod and one to the gage support. The movement of the free light relative to the fixed one was recorded by the streak camera. Pre- and post-test conditions of the walls were recorded by still photography. Also, 16mm pictures and high-speed (3000pps) cameras were used, however the speed of the cameras was sogreat, only the fireball and resulting

smoke were recorded.

TEST SETUP

Wall No. 1 was tested three times and Wall No. 2 only once. The explosive in each test was composition C-4. The height of the center of each charge was 1.22m (4ft). Table 1 shows the test plan for the model and equivalent parameters for the prototype.

TEST RESULTS

Test Numbers 1&2 (Wall 1)

The first test resulted in relatively minor damage. There was some slight spalling immediately in front of the explosion and minor hairline cracks at the top of the haunch. The second test resulted in increased spalling and cracking damage. The greatest damage was the failure of the vertical reinforcement at the top of the haunch.

Test Number 3 (Wall 1)

This was the last test of Wall No. 1. The explosive charge was 113kg (250 lbs). The depth of the crater went beyond the depth of the nearside reinforcement over the middle quarter of the wall (Fig 3). The soil displacement behind the Wall (Fig 4) minimized the load distribution, causing relatively large wall displacements. Damage to the earth mound was minimal.

Test Number 4 (Wall 2)

The only test of Wall 2 involved 227kg (500 lbs) of explosive. Significant damage was sustained by the wall; the middle third was completely destroyed (Fig 5). Debris from the breakup was sent approximately 100m (330 ft) behind the barricade. The size of the fragments creates a hazardous situation for structures within intraline distances.

CONCLUSIONS

The single charge capacity was definitely greater than the 113kg (250 lbs) used in Test 3, but smaller than the total of the first three tests, 204kg (450 lbs). Overpowering of the system was demonstrated in Test 4 where the damage can be considered as a structural failure.

It can be concluded that a full scale earth-mounded

single revetted barricade (conforming to AMCR 385-100) with dimensions equal to three times those of the test structure, would have an upper explosive limit on the order of 3600 to 4500kg (8000 to 10,000 lbs) when a minimum distance of 3.66m (12ft) between the wall and center of the charge is maintained. If reflective surfaces or confinement greater than that of a single barricade exists, the increased blast output will reduce the explosive limit. However, if the charge is distributed into several smaller charges, then either the charge capacity will increase for a given separation distance or the safe separation distance will decrease for a given total explosive quantity.

BELOWGROUND CELL

TEST STRUCTURES

Two cells were built for this series of tests also. Each structure was constructed of reinforced concrete positioned belowground, and the top level with the ground surface. As shown in Figure 6, the size of the structure is representative of a one-third scale model of a typical belowground operating building. Each cell was cubic in shape, with fourwalls and foundation slab. The interior dimensions were 2.44m (8ft) cube while the concrete thickness of each wall was 0.2m (8in) and slab, 0.25m (10in). The amount of reinforcement was determined by considering the structures' capacity to sustain the exterior soil pressures and complied with the minimum flexural reinforcement as specified in TM5-1300 (Ref 3). Laced reinforcement was not used in these walls. At the top of each structure was a reinforced concrete apron (Fig 7), continuous around the structure, and cast monolithically.

In order to avoid an elaborate and complicated installation of deflection instrumentation, the cells were positioned partly below the natural terrain and backfilled around that portion extending above the ground. The backfill was extended horizontally in all directions a distance sufficient to duplicate infinite soil conditions, then allowed to slope at a rate of 2 to 1.

INSTRUMENTATION

Only one of the four walls of each cell was equipped with electronic displacement gages. The gage setup was the same as it was for the barricade tests. Hand measurements and still photographs were also taken. Two cameras with a speed of 3000pps and one with a speed of 500pps were used. Soil movement was determined with poles which were placed in the backfill (Fig 7).

TEST SETUP

Of the ten tests conducted, the first eight can be considered as response test to determine the maximum charge capacity of the structure. The test plan is shown in Table 2. The first seven tests (on Cell 1) were with progressively larger charges to attempt to establish the upper explosive limit. This upper limit was then used as the explosive quantity for Test 8 on Cell 2. Both cells were severely

damaged after these tests, but had not failed. Additional test were conducted on both cells with the concrete aprons removed in order to establish the magnitude of the structure's capacity if the aprons were eliminated. The explosive used in Tests 1-8 was Composition B. In Tests 9&10 Composition C-4 was used.

TEST RESULTS

Test Numbers 1-5 (Cell 1)

In Tests 1-3, in which 0.9, 2.7, and 2.7kg (2, 6, 6 lbs) of explosive were used, damage was relatively minor. Hairline cracks were visible in the vertical corners. No sign of soil movement was observed in Tests 1&2. In Test 3, slight movement of the soil occurred. Test 4, with 11.2kg (25 lbs), resulted in increased spalling, widening of cracks, and plate action on the part of the walls. In Test 5, with 19.5kg (43 lbs), previous damage was more pronounced, vertical bars at the jumction of the walls and floor slab were visible, as were vertical and horizontal bars in the corners. Upheaval of the backfill also occurred.

Test Numbers 6&7 (Cell 1)

For Test 6, 28.8kg (63 lbs) was detonated. Concrete was broken loose to the full thickness of the wall in the corners. Vertical reinforcement at the corners was pulled towards the cell interior and all bars at the base of the wall were visible, several were broken. Soil was displaced near the first row of poles. In Test 7 (36.9kg (81 lbs)), debris from the breakup of the walls at the corners was formed. All reinforcing bars at the corners were exposed (Fig 8) and earthfill fell into the cell. Uniform curvature of the walls was observed. This is due to the support provided by the soil over the full area of the walls. Concrete sections weighing 1kg (2.2 lbs) or greater were thrown out from the cell for a distance of 4.57m (15ft); smaller sections went farther. The apron was badly damaged in the corners.

Test Number 8 (Cell 2)

A total of 86.7kg (191 lbs) was detonated in this test, the first in Cell 2. Damage is shown in Fig 9. Excessive spalling and separation of concrete from the reinforcement took place. Pieces of concrete weighing up to 4kg (8.8 lbs) were thrown as far as 10m (33ft). Most of the horizontal bent reinforcing at the corners and the bars at the junctions of walls and the floor were broken. Soil was displaced from the edges of the apron and loosened up to a

distance of 3.66m (12ft) away.

Test Number 9 (Cell 1)

For this test, the concrete apron was sawed off and 68kg (150 lbs) of Composition C4 detonated in the center of the cell. More concrete was removed from the corners. In general, complete failure did not occur and the structure functioned as an effective barricade, although fragments were produced. Damage is shown in Fig 10. The deflections at the top of the wall were considerably larger in this test, due to the fact the apron was removed.

Test Number 10 (Cell 2)

The apron was also removed from this cell before testing with 113kg (250 lbs). This cell had been tested only once, with 86.7kg (191 lbs). Structural damage in this test (Fig 11) was considerably greater than in Test 9. Two walls completely failed while the others were on the verge of failure. A considerable amount of concrete debris was dispersed distances greater than barricaded intraline distances, with smaller ones being projected beyond unbarricaded distances. The degree of damage was beyond incipient failure. Qualitatively it can be said the charge capacity of this type of structure will be less than the combined weights used in Tests 8&10 or 200kg.

CONCLUSIONS

These series of tests have indicated that when subjected to the effects of an internal explosion, belowground structures with no hardened roof will have a maximum explosive charge capacity beyond which they will fail. This capacity is less than that which was considered in most past facility designs. Also belowground cells with concrete aprons exhibit an increase in blast resistant capacity.

For belowground structures with overall dimensions equal to three times those of the test structure, the upper explosive limit will be on the order of 2700 to 3600kg (6000 to 8000 lbs) when the charge is at the center of the structure and it has a concrete apron or some similar system for beam action. Belowground cells with light frangible roofs will have an explosive capacity roughly the same. However, those without aprons and/or with multiple charges will have decreased explosive capacities.

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1. Dobbs, N., et al, "Blast Capacity Evaluation of Single Revetted Barricades", PA Technical Report 5009, Picatinny Arsenal, Dover, New Jersey, November 1976.

2. Arya, R, et al, "Blast Capacity Evaluation of Belowground Structures, "Contractor Report ARLCD-CR-77006, US ARRADCOM, Dover, New Jersey, May 1977.

3. "Structures to Resist the Effects of Accidental Explosions, (with Addenda)", TM5-1300/NAVFAC P-397/AFM 88-22, Department of the Army, the Navy and the Air Force, Washington, DC, June 1969.

4. "Safety Manual", Army Materiel Command Regulation AMCR 385-100, Headquarters, US Army Materiel Command, Washington, DC, April 1970 (with 14 October 1971 and 12 September 1974 changes).

Table 1 Test Plan

For Single Revetted Barricade

Test No.	Wall No.	1/3 Scale Model Charge WT kg (lb)	1/3 Scale Model Standoff m (ft)	Full Scale Structure Charge WT kg (lb)	Full Scale Structure Standoff m (ft)
1	1	23 (50)	1.22 (4)	612 (1350)	3.66 (12)
2	1	68 (150)	1.22 (4)	1837 (4050)	3.66 (12)
3	1	113 (250)	1.22 (4)	3062 (6750)	3.66 (12)
4	2	227 (500)	0.91 (3)	6120 (13,500)	2.74 (9)

NOTE: Height of center of each charge above floor slab was 1.22 m (4 ft)

Table 2. Test Plan for Belowground Cell

Test No.	Cell No.	Charge Wt. [1]		Full Scale Equiv	
		kg	lbs	kg	lbs
1	1	0.9	2	24	54
2	1	2.7	6	73	162
3	1	2.7	6	73	162
4	1	11.2	25	302	675
5	1	19.5	43	527	1161
6	1	28.8	63	778	1701
7	1	36.9	81	996	2187
8	2	86.7	191	2341	5157
9 [2]	1	68.0	150	1836	4050
10 [2]	2	113.0	250	3051	6750

NOTE: 1. Charge was placed at center of cell
2. Concrete apron sawed off

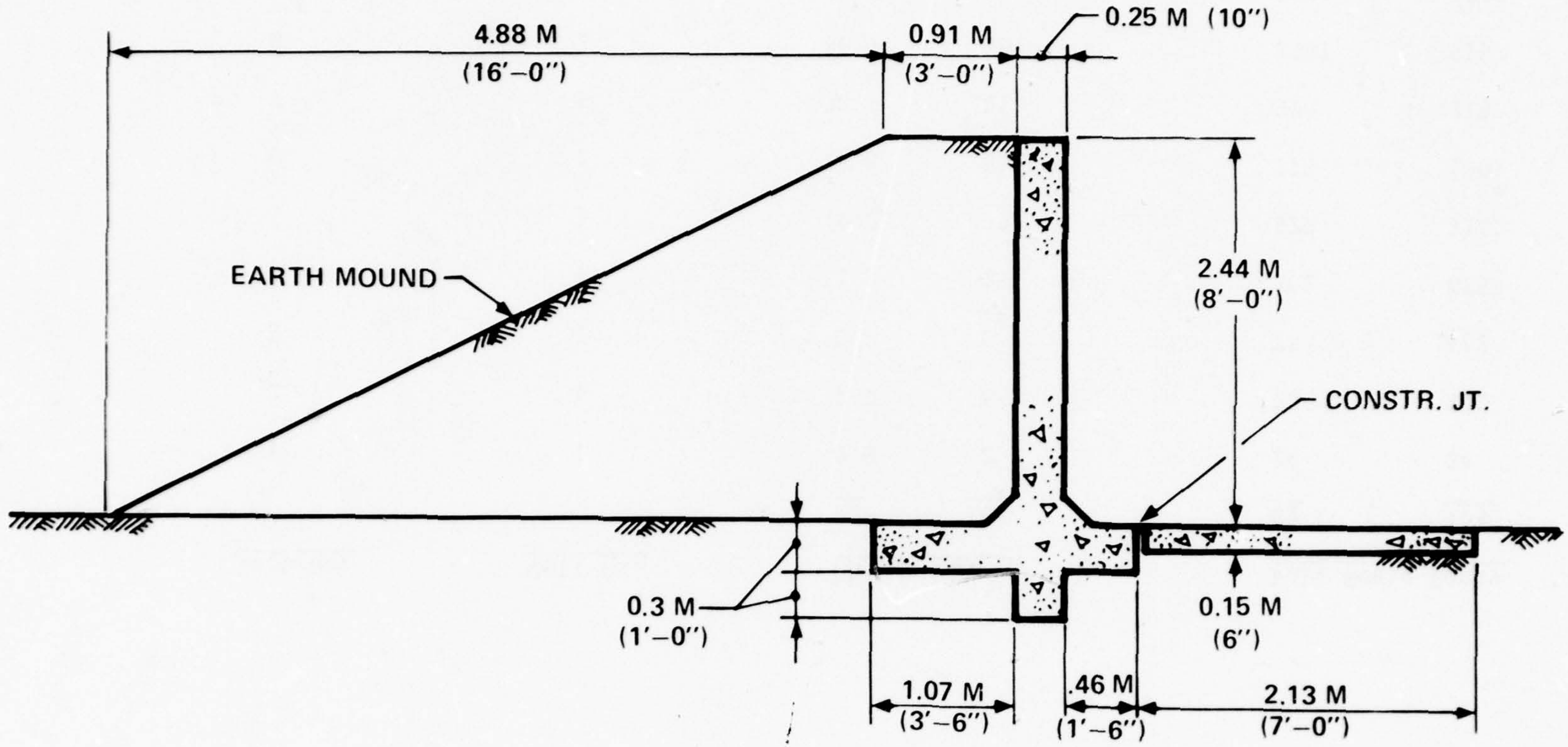

Fig 1. Layout of Single Revetted Barricade test structure

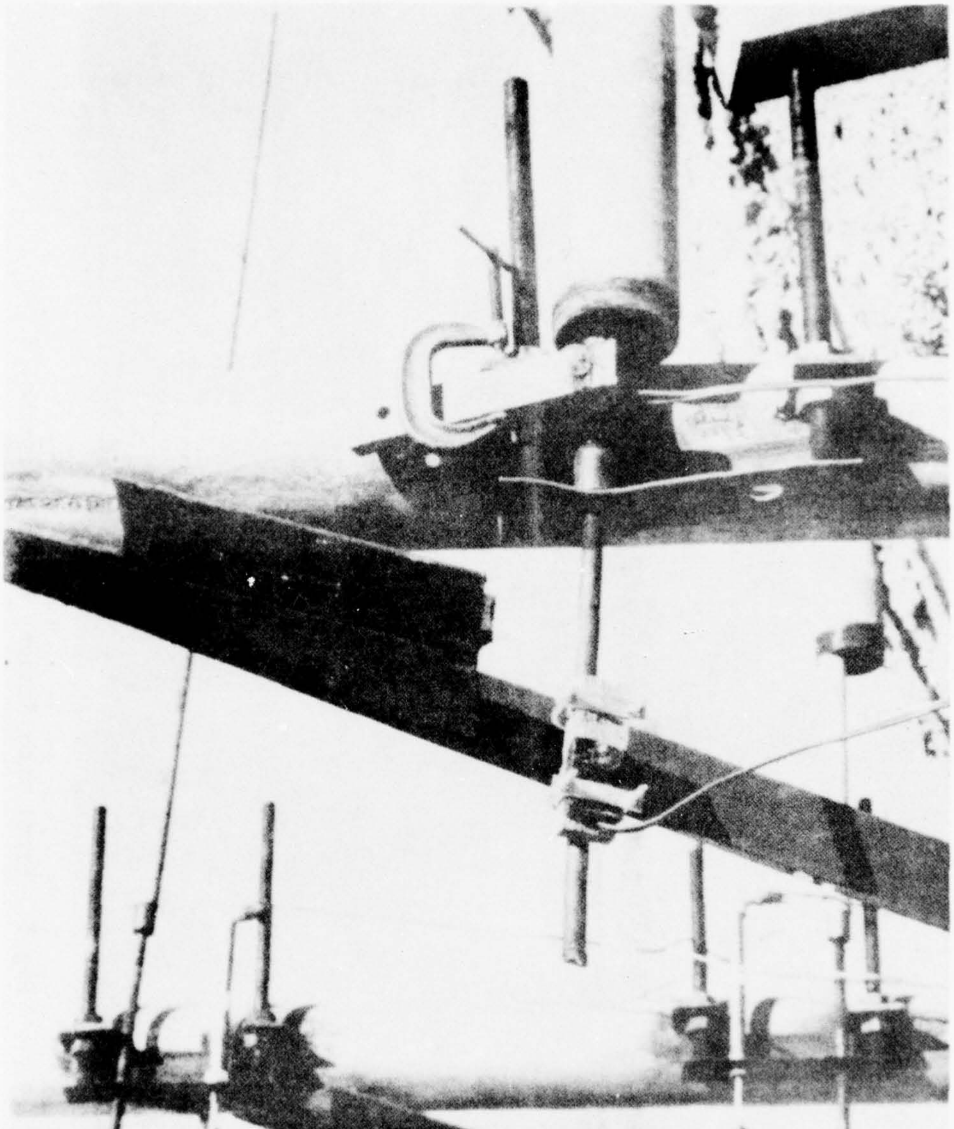

Fig 2. Deflection gage and support

Fig 3. Front face damage, Wall 1, Test No. 3

Fig 4. Soil displacement at top rear of Wall 1, Test No. 3

Fig 5. Front face damage, Wall 2, Test No. 4, 227 kg

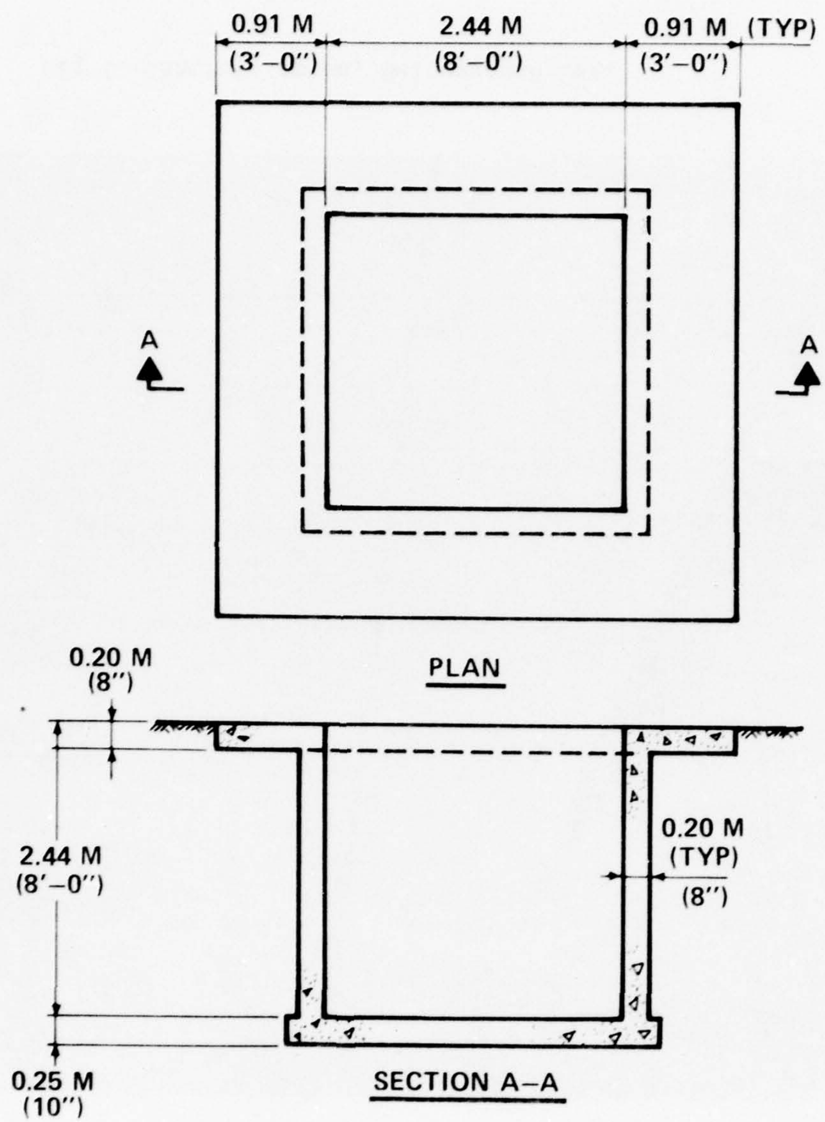

Fig 6. Layout of Belowground Cell test structure

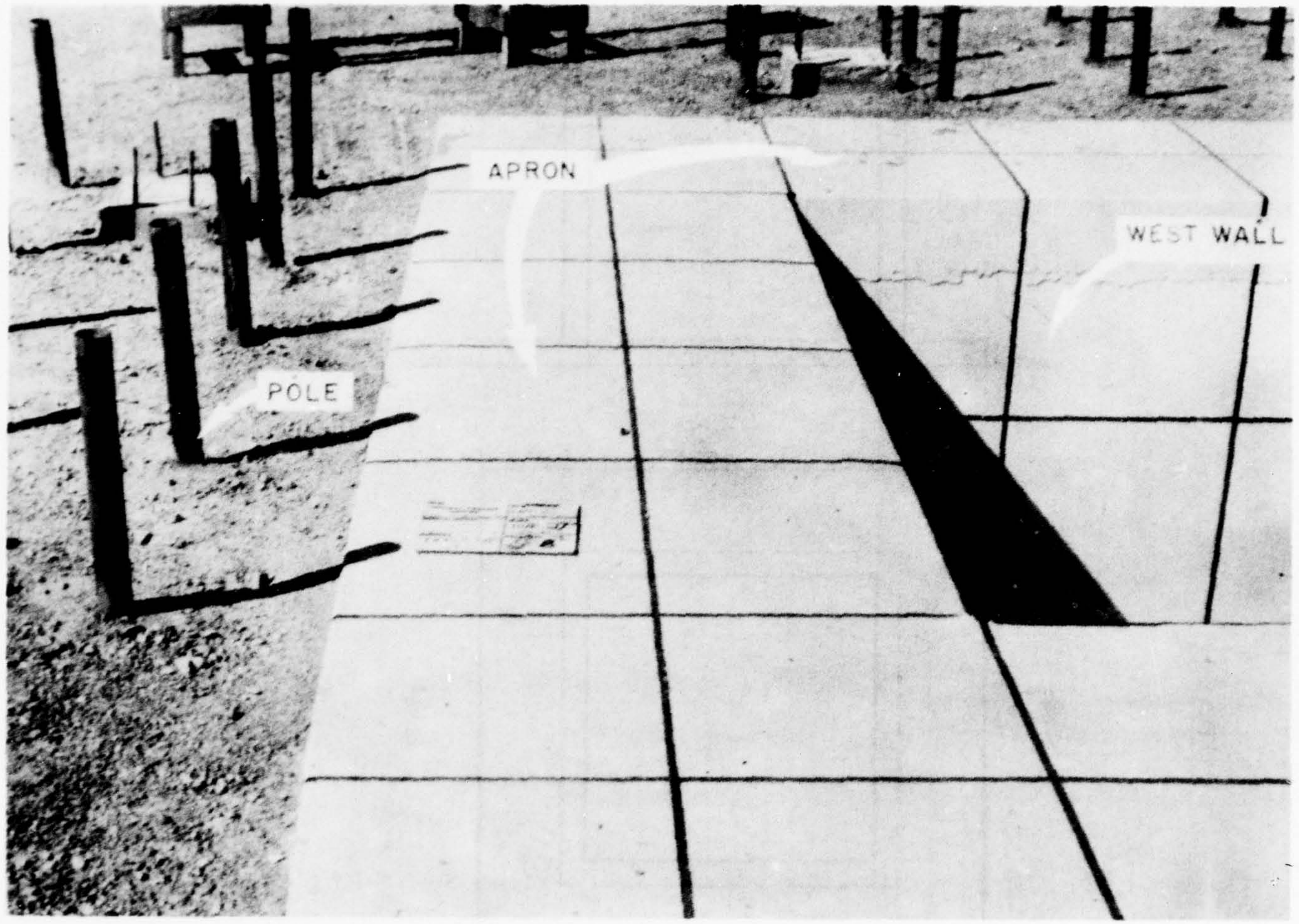

Fig 7. Concrete apron, Belowground Cell

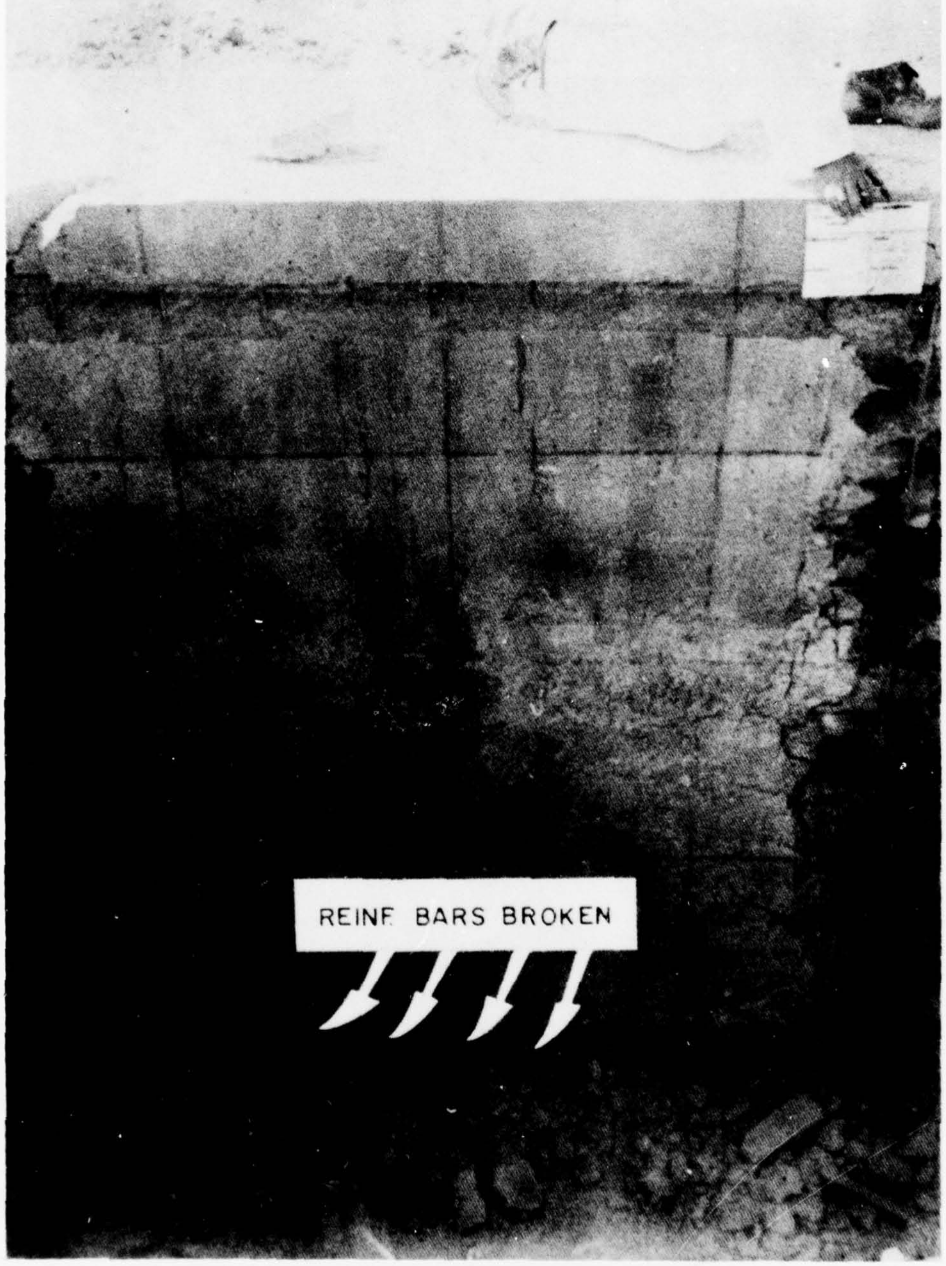

Fig 8. Damage to Cell 1 after
Test No 7.

Fig 9. Damage to Cell 2 after Test No. 8

Fig 10. Damage to Cell 1 after Test No. 9

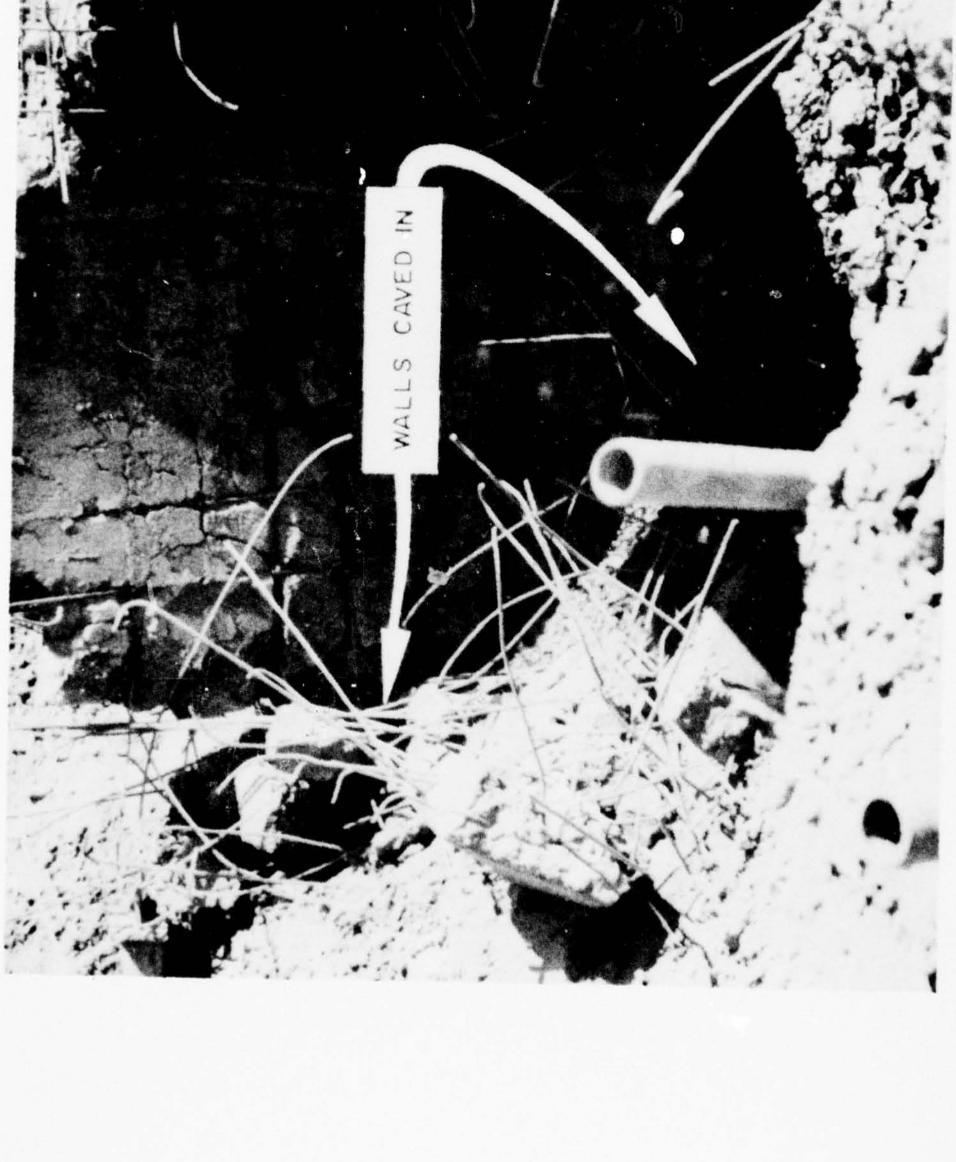

Fig 11. Damage to Cell 2 after Test No. 10

Tests on the Effects of Explosive Charges on Reinforced Earth Walls

By: Victor Elias[1]

In the last decade over 1500 Reinforced Earth structures have been built worldwide with over 150 structures completed in the U. S. Initially, the utilization of Reinforced Earth was limited to highway retaining structures in areas of difficult terrain, but it was soon realized that important other uses promised economy and made available certain technical advantages over traditional methods of construction.

The principle of Reinforced Earth has been extensively described by Vidal[1][2] its inventor, Schlosser[3][4] and others in the literature and a summary of the state-of-the-art (1978) was presented by Lee[5].

Aside from economy, the principal technical reason for using Reinforced Earth structures is their unique ability to withstand post construction movements both vertical and horizontal whether induced by foundation settlements or strong ground motion caused by either a natural or man made seismic events.

To date a number of protective blast structures have been built or are under design at various worldwide locations. All of these structures have been designed by one of the worldwide family of Reinforced Earth Companies, licensed by the inventor, which provide the design, specifications and the prefabricated materials of construction. Reinforced Earth applications are covered by U. S. patents issued to Henri Vidal[6].

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(1) Vice President, Engineering. The Reinforced Earth Company, Washington, D.C.

reinforced earth ®

The design further considers that if a failure wedge develops it will occur in the unreinforced fill beyond the reinforced volume, thereby treating the reinforced fill as a single gravity unit. The application of surcharges such as from seismic events requires the calculation of the additional tensile forces which the reinforcing strips must resist due to this additional load, as schematically shown in Fig. 1.

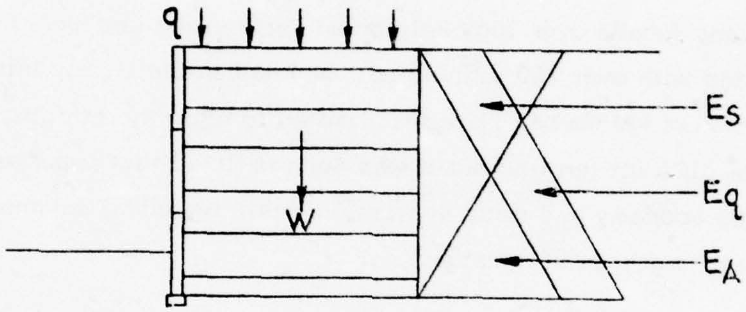

Fig. 1 Schematic of Forces on a Reinforced Earth Structure

Where:

- q : is a surcharge load
- W : is the total weight of the Reinforced Earth mass
- E_A : is the horizontal pressure due to earth pressure
- E_q : is the horizontal pressure due to the surcharge
- E_S : is the pseudostatic horizontal pressure due to a seismic event

II. DESIGN METHODS

The present design method requires that the external mass stability, as shown on Fig. 1, based on initial proportioning is checked by conventional static methods prior to internal stability design. For structures not subjected to large surcharge loads the length of reinforcing strips are generally chosen at

The development of both quantitative and qualitative data as to the performance of Reinforced Earth structures subjected to blast forces and overpressures was undertaken jointly in 1975 and 1976 by The Reinforced Earth Company of France and the Buildings, Fortifications and Works Investigative Board of the French Army in collaboration with the National Gunpowder and Explosive Company and the Spanish Rio Tinto Company. The results and conclusions from these investigations are the subject of this paper.

The behavior and design of Reinforced Earth structures subject to ground motions associated with major earthquakes was studied in detail by Lee, Richardson, et. al.(7). Resulting from these and other research efforts, design methods have been established to insure stability under such loadings and to limit deflections to within design tolerances.

I. DESIGN PRINCIPLES

The key element in Reinforced Earth is the friction between the earth and the reinforcements. Through this friction, the earth transmits to the reinforcements the stresses which develop in the mass. The reinforcements are thereby placed in tension and the composite material gains an pseudocohesional strength which is directly proportional to the tensile strength of the reinforcements and acts in the direction of their placement.

The design of Reinforced Earth structures, at present, consists of considering the local equilibrium between the facing elements and the reinforcing strips under the assumption that the reinforced volume is in a state of limit equilibrium and that the principal direction of the stresses are vertical and horizontal. The reinforced backfill is treated as a composite material that has both the frictional strength of the granular soil and the pseudocohesion imparted by the reinforcement.

70% of the wall height, except that a minimum length of 14 feet is necessary regardless of size of wall to insure integrity.

Specifically, the checks for external mass stability consist of determining the adequacy of the mass against overturning moments generated by earth pressure and other imposed loads as well as sliding stability along the interface with the foundation soils. Consistent with the above, bearing capacity analyses for both general and local shear are made using Meyerhoff theory for bearing capacity of foundations under eccentric loadings.[8] It should be noted that the relevant factor of safety is computed with respect to the ultimate bearing capacity of the foundation and should not be confused with more conventional foundation analyses for rigid structures which generally compare the imposed loads to an allowable bearing capacity. This latter capacity in cohesionless soils is usually established to limit settlements, which are not a problem for flexible structures such as Reinforced Earth.

Internal stability design consists of developing the appropriate horizontal pressure envelope and designing the reinforcing strips for sufficient cross-sectional area to carry the horizontal loads as well as for sufficient surface area to transfer in friction the stresses which develop in the mass. Minimum bond lengths can be obtained under the assumption that the earth-reinforcement friction is fully mobilized, and that the normal stress is uniform and approximately equal to the overburden pressure.

Significant data has been published recently by Schlosser and Elias[9] on the variation of the apparent coefficient of friction f^* used in bond calculations in Reinforced Earth structures. It was shown that the phenomenon is complex in which the density and dilatancy of granular fill are predominant factors as well as the nature of the strip surface. In general, the apparent coefficient of friction f^* is highest in the upper portion of the structure and becomes asymtotic to a value equal to the tan. of $\emptyset$ for ribbed strips where the shear is essentially a soil to soil interface phenomena.

III. TEST SERIES OF HIGH EXPLOSIVE CHARGES ON REINFORCED EARTH WALLS

To qualitatively assess the effects and behavior of Reinforced Earth structures subjected to explosive charges the previously mentioned test program was implemented in France.

Three types of structures were designed using conventional design methods and constructed for this test. Their dimensions are as follows:

A - Single face concrete clad structure approximately 15 feet high and 40 feet wide at the top.

B - Single face, metal clad structure approximately 15 feet high and 35 feet wide at the top.

C - Double face, metal clad structure approximately 15 feet high and 35 feet wide at the top with a total width between faces of 11.5 feet.

The blast test program was conducted using explosive charges made of blocks of PLANP (plastic), where 1 ton of PLANP is the equivalent of 1.25 tons of T.N.T. All charges were placed 0.5 meters below ground level.

The instrumentation program consisted of recording the excess blast pressure at various points along the wall and in neighboring areas and measuring the ensuing deformation of the structure. An attempt was also made to measure the stresses in the reinforcing strips during the blast. The general program of blasting consisted of placing and detonating successive charges of 1 and/or 5 tons of explosive at distances of 10, 4 and 0.5 meters from most structures. Test walls A, B, and C are shown in Figs. 2, 3 and 4.

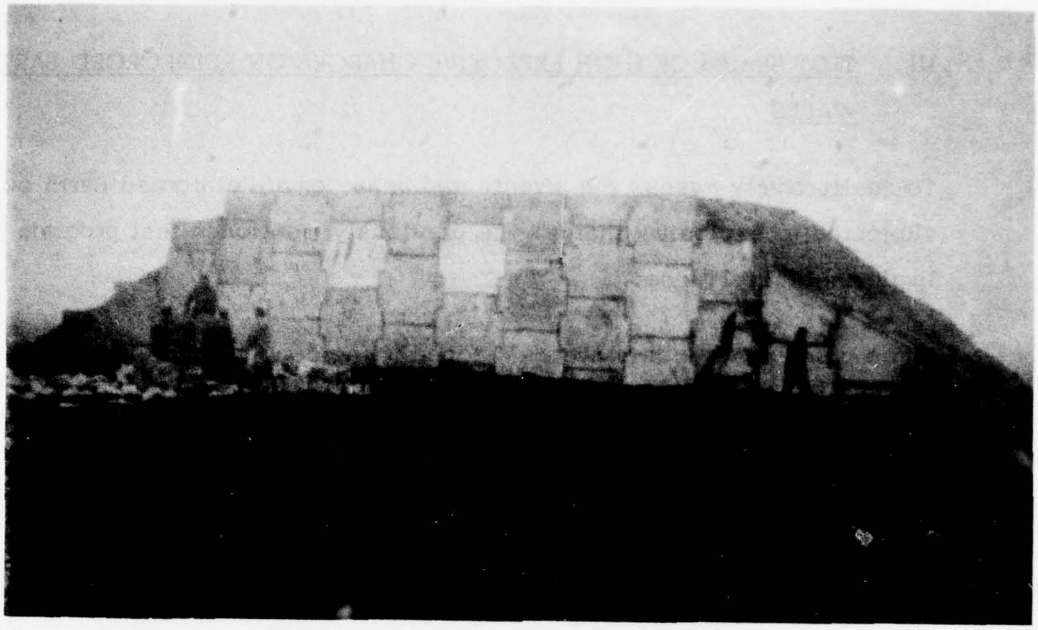

Fig.2 Single Faced Concrete Clad Structure Prior to Testing

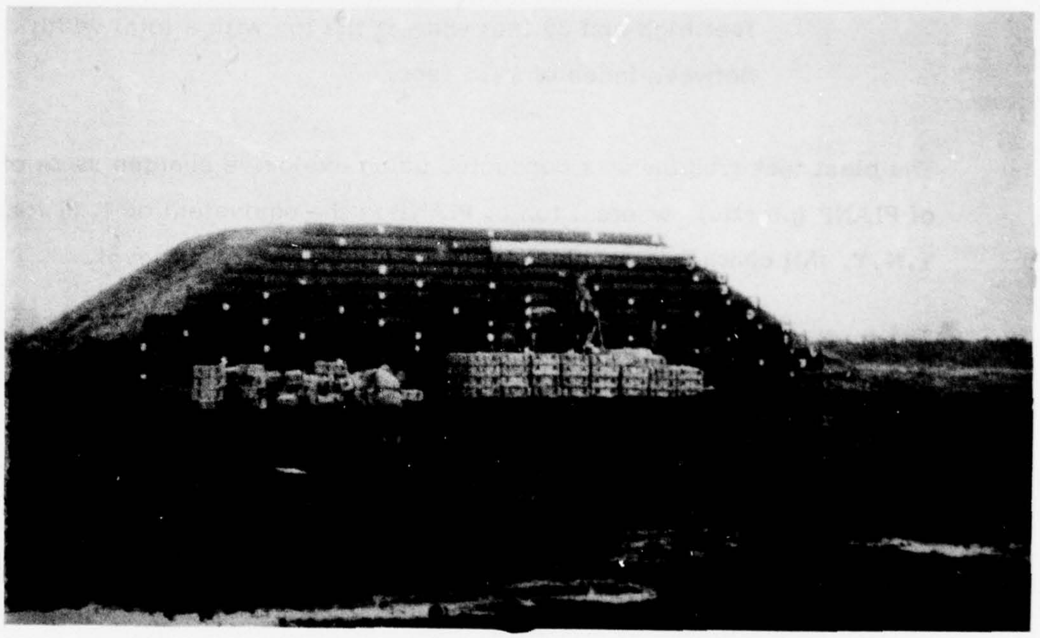

Fig.3 Single Faced Steel Clad Structure Prior to Testing

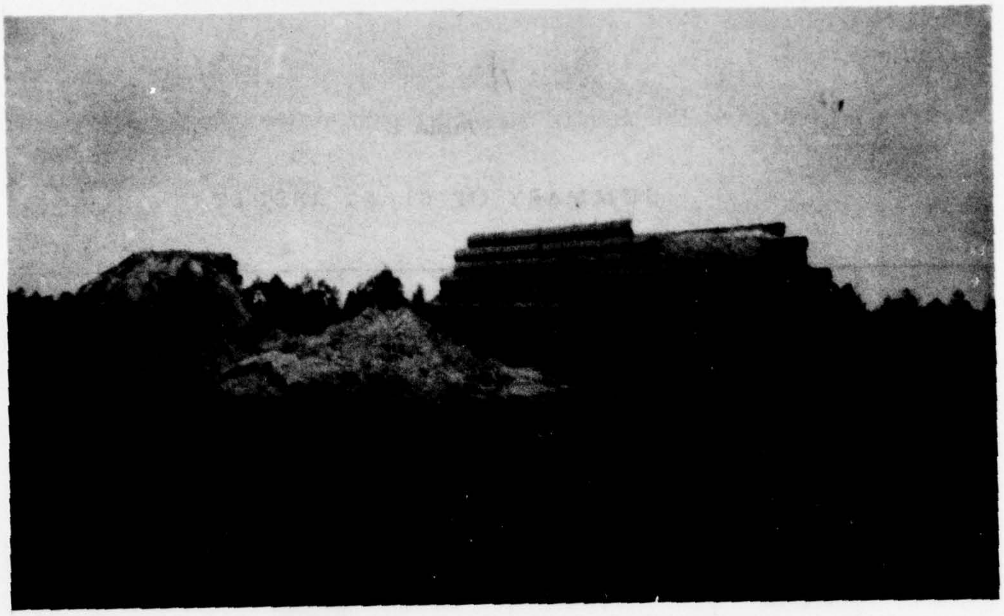

Fig.4 Double Faced, Steel Clad Structure Prior to Testing

IV. SUMMARY OF RESULTS

The tests series were conducted by detonating the charges placed at 10 meters from the structure first measuring the ensuing deflections and then loading and detonating the nearer charges. The generalized results are summarized in Table 1.

Table 1

SUMMARY OF BLAST RESULTS

Facing	Charge	Max. Blast Pressure	Max. Deflection	9" Forces	Projectiles & Remarks
Metal	1^T@10m	50-100 TSF	20"Top 3" Bottom	1.8g	No Projectiles
	1^T@4m	100 TSF	36"Top 14" Bottom	-	No Projectiles - Severe Fracture of Skin
	1^T@0.5m				Projectiles to 15m
	5^T@3.0m			22g	Projectiles to 40m with Parabolic Trajectory, Complete Collapse in Center Portion of Wall
Concrete	1T@1m				Projectiles to 10m
	1^T@4m				No Projectiles

reinforced earth ®

It is quite apparent from the results that Wall A (concrete clad) exhibited excellent behavior under the imposed loadings. Only two cladding elements were projected rearward to a distance of less than 10 meters after the explosion of the 1 ton charge at a distance of 1 meter from the left side of the structure as shown on Fig. 5.

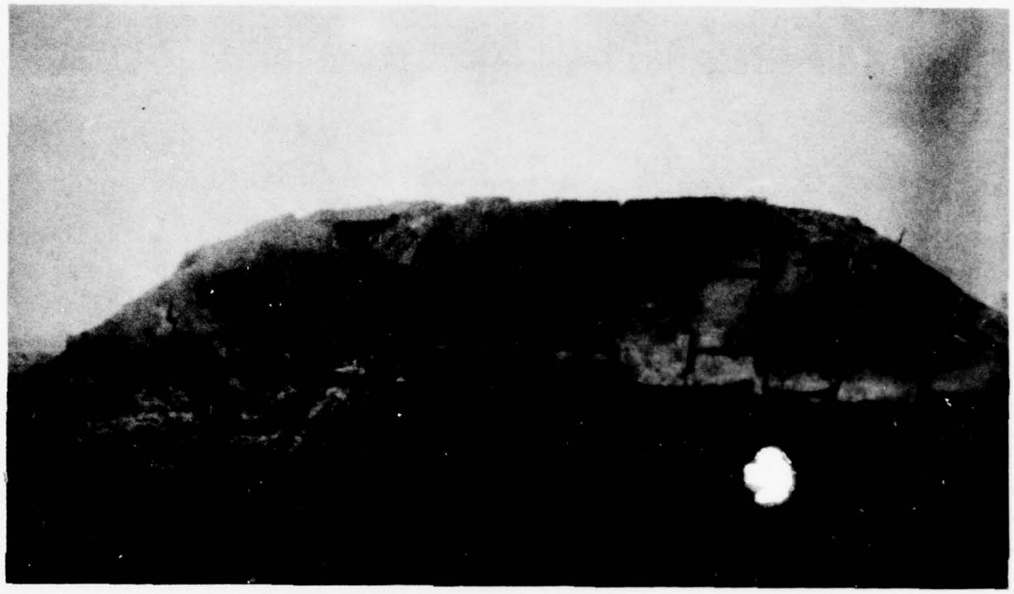

Fig. 5 Concrete Faced Structure After Test Series

Similarly, Wall B (steel clad) exhibited excellent behavior under the imposed loading. Only under the impact of 1 ton charges placed at 0.5 meter from the facing did some skin elements separate and portions of them were projected rearward. Visual damage can be seen on Fig. 6 prior to the loading of the final charge.

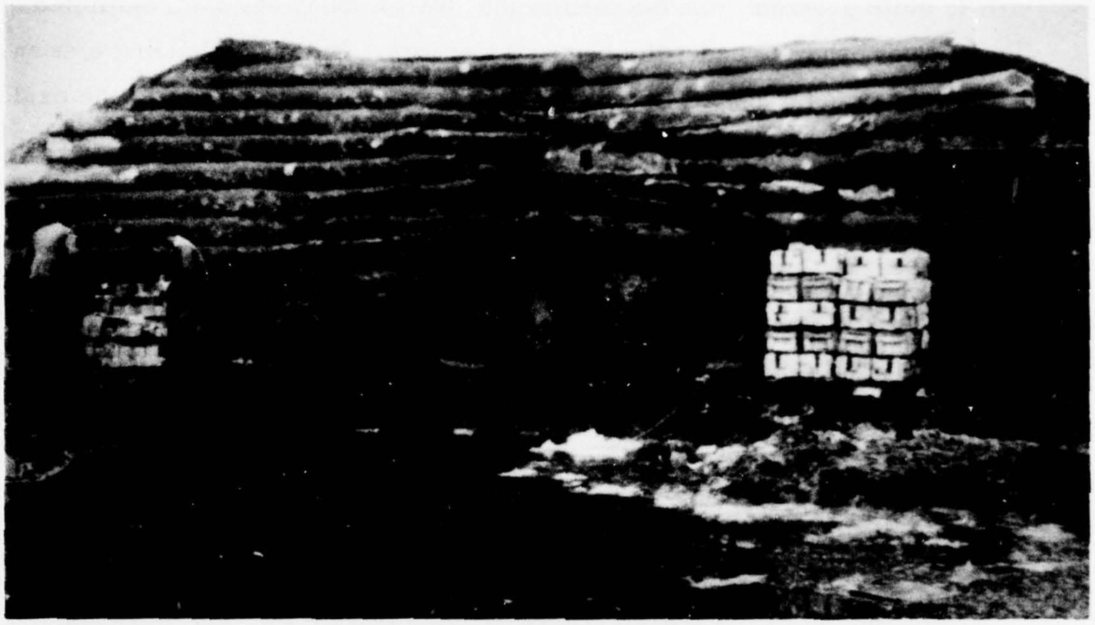

Fig. 6 Single Faced, Metal Clad Structure Prior to Final Charges Placed at 0.5 Meters From Face

The initial test series on the double faced metal clad walls having a width between facings of 11.5 feet indicated that their mass was insufficient to withstand explosive charges of 1 ton placed 4 meters from the facing. The mass tipped over as shown in Fig. 7 but no projectiles resulted from the collapse. An additional series of blast testing was subsequently conducted on a similarly constructed wall where the distance between facings was increased to approximately 15 feet. This latter structure performed satisfactorily as its mass was sufficiently increased.

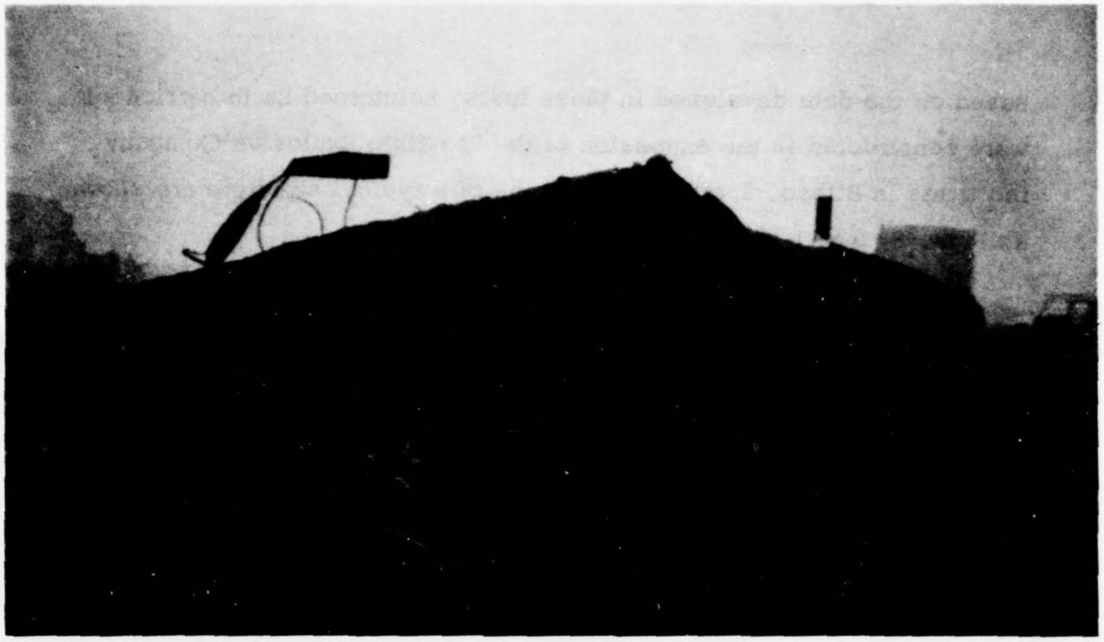

Fig. 7 Double Faced, Metal Clad Wall of 11.5 Feet Thickness Tipped Over After Test Blast

V. CONCLUSIONS

Based on this test series, it was concluded that Reinforced Earth walls with either concrete or metallic facings have performed extremely well when used as protective walls or merlons. The main advantage aside from economy over rigid walls is that their modular construction insures a great degree of flexibility under blast loadings and allows deformations without structural damage. Even under relatively high blast pressures the cladding elements limit the number of projectiles that occur.

For double faced walls the width must be chosen to insure that sufficient mass is available to resist blast pressures and prevent tipping. For blast pressures on the face on the order of 100 T.S.F. a width of at least 15 feet is indicated.

Based on the data developed in these tests, Reinforced Earth barricades were constructed in the expansion of the Rio Tinto Explosive Company facilities in Bilbao, Spain. Photographs of a typical structure are shown as Figs. 8, 9 and 10.

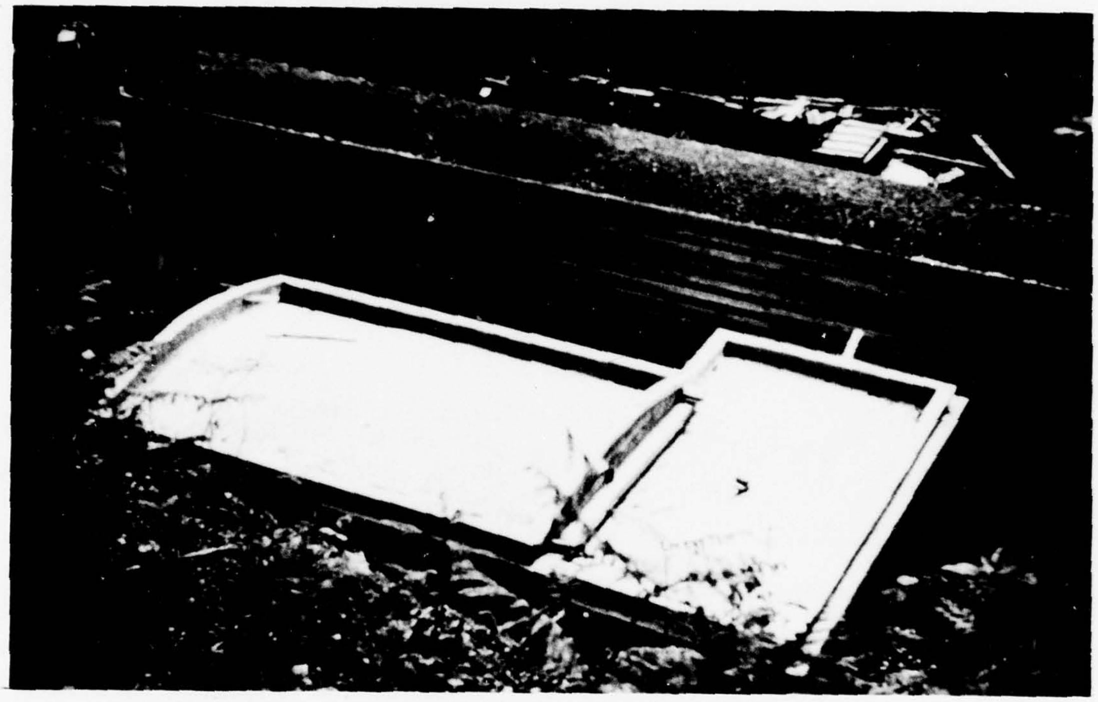

Fig.8 Completed View of Protective Barrier, Rio Tinto Facility Bilbao, Spain

Fig.9 Construction of Protective Barriers

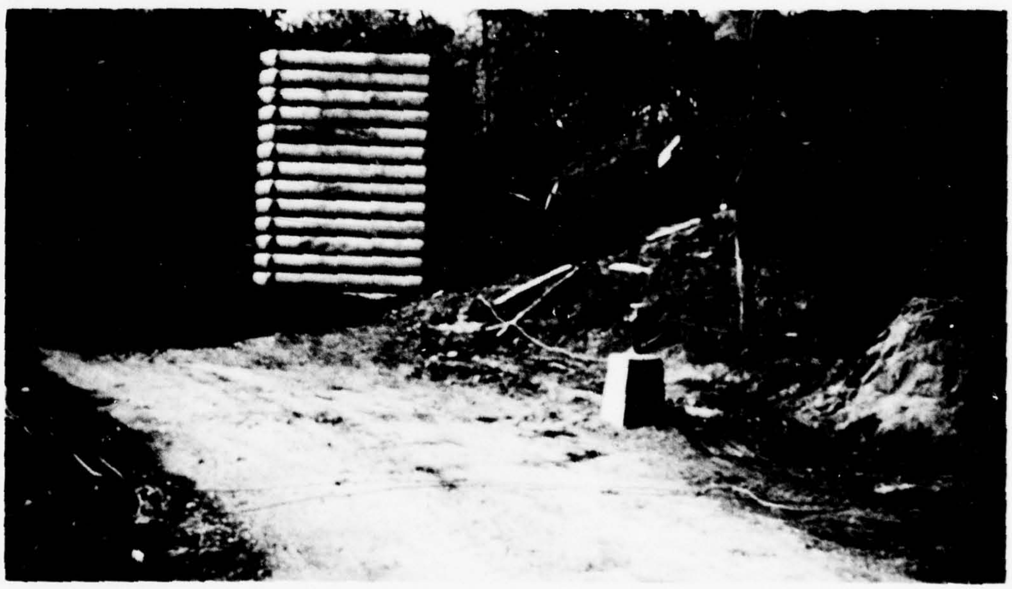

Fig.10 Side View Completed Protective Barricade
Rio Tinto Company Facility Spain

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ULTRA HIGH SPEED FIRE PROTECTION SYSTEMS

FOR AMMUNITION PLANTS APPLICATION

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At the 16th Annual Department of Defense Explosives Safety Seminar we presented a paper on the design of a high speed deluge system to control fires at a new black powder processing facility at Indiana Army Ammunition Plant. Two years ago at the 17th Annual Meeting we demonstrated our capabilities to suppress propane-air explosions in an 18,000 cubic foot pump room aboard the U.S. Coast Guard test ship, the U.S.S. Rhode Island.

Today I would like to talk to you regarding some new innovations in ultraviolet fire detection systems and other applications where ultraviolet detection has been applied.

If you have a high-frequency flash fire problem or the potential such as a volatile liquid transfer point, explosives processing or other chemical process where a flash fire hazard exists, ultraviolet fire detection

systems can and will save you money and possibly prevent serious personal injury to your employees. These systems have one great advantage over other fire detection devices and that is the ultra-rapid response to a flame. The fire detection systems actuate in milliseconds as compared to seconds with the older, conventional activating equipment.

Tests indicate that ultraviolet sensors respond in the 10 millisecond area with water delivery in the millisecond range. The difference in the time between the activation of an ultraviolet system and the conventional system in an explosion or flash fire can mean the difference between a "no loss" incident and an uncontrolled fire.

Ultraviolet detection was selected because it would eliminate the false actuation contributed to other types of optical or radiation detectors and still maintain instantaneous response time. Because ultraviolet detectors respond only to a narrow spectral range, it is easy to reduce the possibility of false signals. The wave length of sensitivity of Detector Electronics ultraviolet detectors is 1850 to 2450 Angstroms. This narrow spectrum of sensitivity prevents our UV sensing detector to detect radiation from sources other than fire. It is also

important to note that radiation from the sun and aritifical lighting does not fall into the detector's region of sensitivity, and due to this feature our ultraviolet detectors can be used in areas of direct sunlight, intense light, either in or out of doors. A very important consideration in applying an ultraviolet sensing device as a fire detector is to know those things that might prevent the device from responding to a fire such as dense smoke which might attenuate the ultraviolet radiation, and also know what sources besides fire that will cause the device to respond, such as welding which produces a large ultraviolet signal or x-ray or gamma rays. Ultraviolet detectors are useful for fire protection applications because they will provide very fast response to the presence of ultraviolet radiation from a flame. Tests conducted for existing arsenal and industrial applications indicate fast burning munitions materials emit tremendous amounts of UV radiation. Therefore, a UV detector is sensitive to a very small ignition even at considerable distances. In addition, it is the only type of sensor that is not affected by wind, rain, snow, extremes of temperature or pressure.

An important innovation made recently by Detector Electronics is the new Automatic Optical Integrity feature known as AO_i, which provides a continuous check to assure that the

entire fire detection system is operational and ready to respond to fire or explosion. A special ultraviolet test lamp inside of each detector housing, but optically isolated from the UV sensor, is turned on sequentially by the controller for each detector in the system. The UV from the test lamp goes through the quartz window, reflects off the beveled ring, and back through the window to the ultraviolet sensor. The signal from the detector is sent to a comparator network in the controller. The network in the controller checks the UV level of signal with the threshold level of the controller. As long as the UV level remains below this level, no fire alarm signal is generated. If a UV signal from a fire or explosion is detected, the threshold level is exceeded and the controller reacts normally. The network also checks the UV signal level from the test lamp to see that it does not drop below a level which would indicate a dirty window. This process automatically checks all of the wiring to the detectors, the quartz window for cleanliness, and the sensitivity of the UV sensor. If a fault develops in the system, the comparator network energizes a digital display in the front of the controller to indicate by code number the exact nature of the fault.

Detector Electronics has also developed an air shield to maintain lens cleanliness while in a contaminated atmosphere. For areas in the munitions industry where powder drying must be supervised by UV detectors, an air shield is used to maintain cleanliness of the lens. The AOi feature described previously is, of course, applicable to these processes to determine if the rate of dust accumulation on the detector windows would cause excessive down time or minimize the fire protection of the system. In addition, the air shield acts as an insulator against high temperature as the continuous flow of instrument air will act as a cooling agent in applications such as powder drying. The detector is held in place by a quick-release ladish clamp for ease of periodic maintenance. The automatic Oi *reflective surface is incorporated* in the air shield so the removal or emission of a detector can be monitored from a control room or incorporated into a computerized security system. Any contamination of optical surfaces or reduction in ultraviolet source intensity or loss of detector sensitivity will be automatically identified as such by the AOi feature and operating personnel can recognize the fault as merely a need for maintenance.

I brought with me today some movies of a powder burning test performed by the Winchester Olin Corporation of East Alton, Illinois for protection on their shell loading equipment.

A series of powder burn tests were performed in order to evaluate an ultraviolet fire detection system. The burn tests were performed at an isolated area at the East Alton Winchester facility. The detection system was furnished by Detector Electronics Corporation of Minneapolis, Minnesota.

A mock-up shell loading machine was fabricated to simulate a center fire parker loader and a detector was suspended above the apparatus along with a sprinkler head. A 1-inch water supply line was available at 40 psi pressure for extinguishment. By counting the film frames, fairly accurate results could be obtained. The sprinkler head was centered 36-inches directly above the burn surface. The ultraviolet detector was suspended to the side and pointed at a 45° angle to the center of the burn surface approximately 10 feet away. A fast burning pistol powder was used throughout. A white paper cover was provided in order to record the length of burn in inches from the point of ignition. Radiating powder trains were placed on the paper and full spread solid pattern was also tried. For the most tests the ignition point was shielded from the detector. Also, two tests were performed with ignition point exposed. Ignition was provided by use of a battery operated electric match.

Various types and size of sprinkler heads were tried as well as varying sizes of solenoid water valves. The detector was wired directly to the solenoid valves so the response was practically instantaneous. The solenoid valve was located at close proximity to the sprinkler head so that there was practically no delay in the water supply.

There were 10 burning tests performed, the first five used a 1/2-inch size solenoid valve and the last five used a 1-inch valve. The 1-inch size showed a definite improvement in extinguishment elapse time. The overall reaction time from ignition to water averaged 0.25 seconds. In actual application, I would consider this slow in comparison to a Squib actuated preprimed valve such as the Grinnell Primac system.

Due to the allotted time, I have taken two tests from the Olin film to show to you today. Although the tests were considered successful, I think you should note that faster extinguishment of the ignited powder could have been accomplished by a larger water supply and denser spray nozzle. To illustrate this I have added some film clips of tests performed at our test facility.

We are currently making a movie to illustrate our detection capabilities. The following film clips I thoughtwould be of interest to you.

In order to illustrate the speed of a fast water deluge system activated by ultraviolet detection, a test was conducted and filmed with high speed and normal photographic equipment. A train of fast burning material consisting of super-fine black flash powder was used. The train of powder was approximately 4 feet long, 4 inches wide and 3/4 of an inch deep. The powder was ignited by an electric match on the right end of the train. A pressurized portable water deluge system containing 2 quarts of water was mounted 18 inches above the center of the powder train with a squib type valve for quick opening and release of water. The detector was mounted above the train of powder on the left, about 6 feet from the electric match.

Upon ignition, a huge black powder fire was observed with a large amount of smoke. The fireball is rapidly extinguished and the cloud becomes steam. After the smoke and steam clear, the burn path can be measured and the speed of response can be approximately determined. Estimated time for complete extinguishment was approximately 30 milliseconds.

To further illustrate fast fire detection using ultraviolet detection, we tossed a torch into a wooden cubicle containing a gasoline filled pan 5 feet by 3 feet. The UV detector was mounted to the roof of the box looking downward. You will see the torch entering into the box and into the detector's cone of vision, which then instantaneously activates a 10 pound Halon bottle and extinguishes the torch prior to its dropping into the pan. You will observe the extinguishment of the torch at various film speeds and camera angles.

This is the identical test as seen previously without any time delay. In order to show both the capabilities of a Halon suppression system and also how critical it is to have fast fire detection, a 200 millisecond time delay was introduced into the detector's electronic circuit. The film indicates how large a fire can become in a short time and then becomes harder to extinguish. Fast detection is required to make extinguishing systems of higly combustible materials effective in those applications.

The last film clip represents a Halon extinguishing system suppressing a gasoline fire bomb or Molotov cocktail thrown into a cubicle or room. In order to prevent the extinguishing

system from actuating from the wick of the fire bomb, a 100 millisecond delay was introduced into the system. This film illustrates the intensity of the fire which would evolve from a gasoline fire bomb.

It again indicates that only fast detection will enable the extinguishing system to suppress this type of a fire.

FIRE MANAGEMENT IN MODERNIZED ARMY AMMUNITION PLANTS

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Paper to be Presented at the Department of Defense Explosives Safety Seminar, September 12-14, 1978

ABSTRACT

In support of the U.S. Army Plant Modernization Program,a series of projects has been carried out to develop water deluge fire suppression systems for use by the GOCO plants. Each of the projects has been successful in demonstrating that rapidly activated water deluge systems can be effectively used to suppress and extinguish propellant fires, and in other applications can be equally effective to combat extraneous fires as may be caused by a large scale detonation. This paper will present an overview of the techniques which have been developed to combat fires as they might occur in the following in-plant operating procedures:

- 105 mm, M-67 bag loading operations, including the hopper (loose M-1 propellant), the line conveyor (single bags of M-1), and accumulators (stacked bags of M-1),
- Closed airveyors conveying M-1 propellant,
- Handling and processing lead azide explosive, including unpacking, kneading, and buggy transport,
- Conveying boxed base-pad and center-core ignitors,
- Conveying cardboard boxes containing 60-lb. of Composition B,
- Loose Composition B being conveyed on a Serpentex conveyor.

ARRADCOM - Contract No. DAAA21-76-C-0255

FIRE MANAGEMENT IN MODERNIZED ARMY AMMUNITION PLANTS

Introduction

Under an ARRADCOM MM&T program, a series of projects has been carried out to develop water deluge fire suppression systems for use by the newly modernized GOCO plants. Each of the projects has been successful in demonstrating that rapidly activated water deluge systems can be effectively used to suppress and extinguish propellant fires, and in other applications, can be equally effective to combat extraneous fires as may be caused by a large-scale detonation. Figure 1 briefly states the purpose of the program. Several GOCO plants have urgently requested that information related to their modernization projects on extinguishing accidental fires be furnished. The data gathered from the experimental evaluations thus far have been immediately incorporated into the designs of the modernized GOCO plants. Although the development program is less than one year old, some of the design parameters are now in use by the Indiana AAP for extinguishing M1 propellant fires in accumulators and hoppers; the tests have resulted in the elimination of expensive fire gates with the deluge system at Radford AAP and steps are now underway to provide water deluge protection for lead azide production in the Lone Star, Kansas and Iowa AAP's.

Each of the above problem areas which have been studied thus far required a separate evaluation program because of the different quantities of material involved, differences in the degree of confinement, differences in the modes of ignition and propellant geometries, and specific constraints dictated by the water pressure and water adequacy problems at each ammunition plant.

The subsequent discussion will review the programs which have been conducted to date, and will attempt to identify the design parameters for the various plant applications which have been established. Those applications which have resulted in significant dollar savings far exceeding the cost of the programs will be identified.

FIGURE 1

WATER DELUGE APPLICATION IN MUNITION PLANTS

PURPOSE: To Evaluate Effectiveness Of Water Deluge Applied To

- Quenching And Extinguishing Propellant Fires
- Prevention Of Propellant Fires Transcending To Detonation
- Extinguishing Fires After Explosive Detonation

To discuss the initial investigation of water deluge systems, two separate phases of the exploratory program should be explained. One deals with a "hardened" water deluge system and the second deals with a "conventional" deluge system. A "hardened" deluge system is one that would be used where a detonation, as opposed to a deflagration, would occur. In order to protect from extraneous fires that could be ignited in the plant as a consequence of a prior detonation, one must use a deluge system that has been hardened against blast and fragments. A conventional deluge system is typified by the overhead water sprinkler system that can sustain intense heat and slight pressure rises, but cannot sustain blast and fragments.

Hardened Deluge Systems

To discuss a hardened deluge system, first consider Composition B in cardboard boxes moving along a conveyor line in the Lone Star or other LAP ammunition plants. In this particular system, the plan of the test was to detonate one box (the donor) of Composition B, and to design a deluge system that could sustain this blast and the subsequent fragments, yet still be able to function and put out extraneous fires as they might occur. Figure 2 shows a mock tunnel and two boxes of Composition B moving along a simulated assembly line. Here we have used a conveyor under the donor box to simulate secondary fragments which might cause a detonation of the second (acceptor) box. These two boxes have been set at a previously established 12 feet minimum safe separation distance. It is assumed that we will not get propagation of a detonation due to blast or fragments, but propagation could occur due to fire. To simulate the tunnel through which this material is being conveyed, a wood and fiberglass tunnel was constructed and a hardened deluge system was installed below the floor level.

Figure 3 shows this deluge system in operation. The nozzles of the system have been placed opposing one another and the two streams of water interlace much like interlaced fingers so that there is complete coverage over the full length of tunnel.

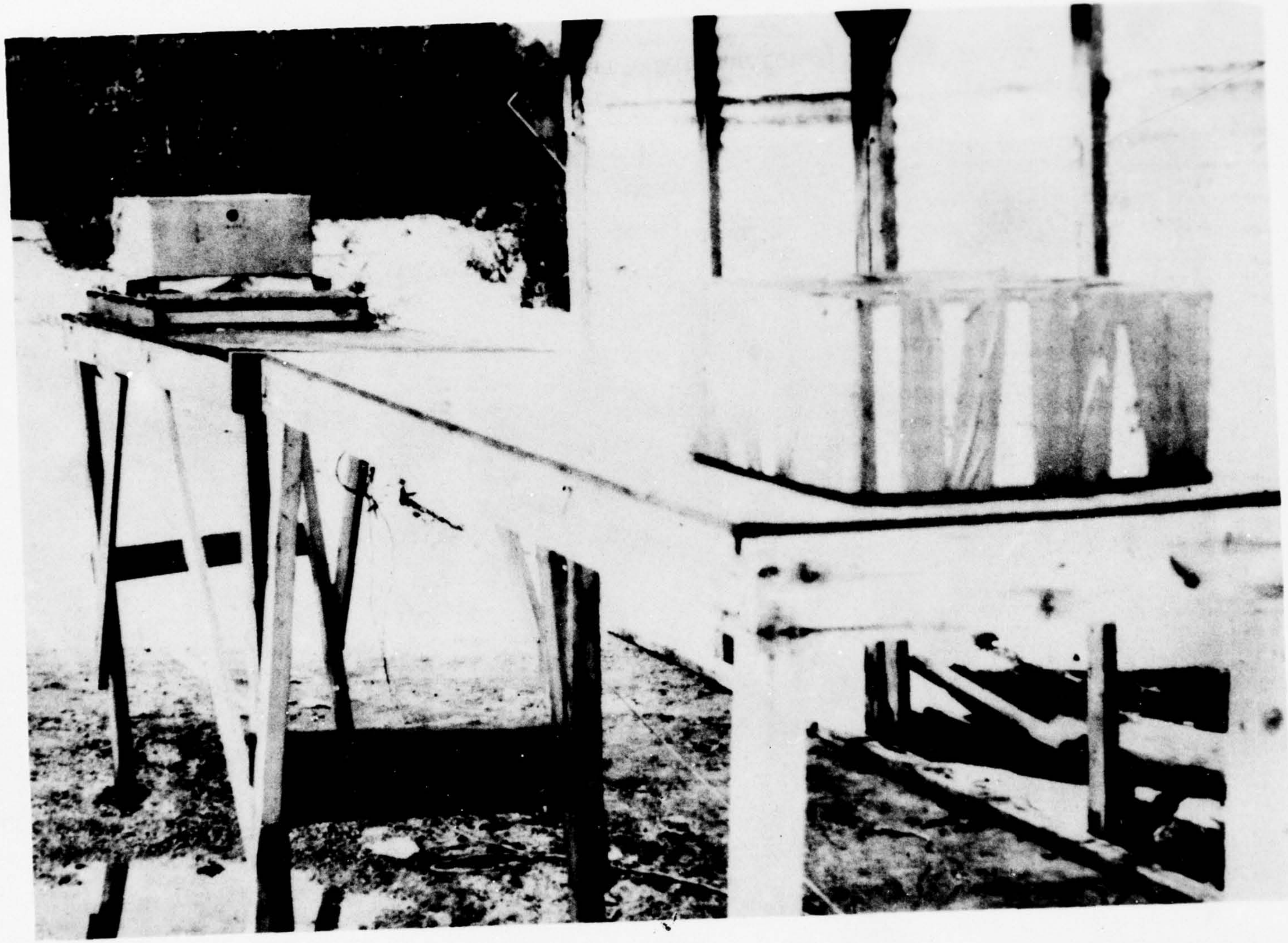

FIGURE 2. SIMULATED CONVEYOR LINE FOR COMPOSITION B EXPLOSIVE

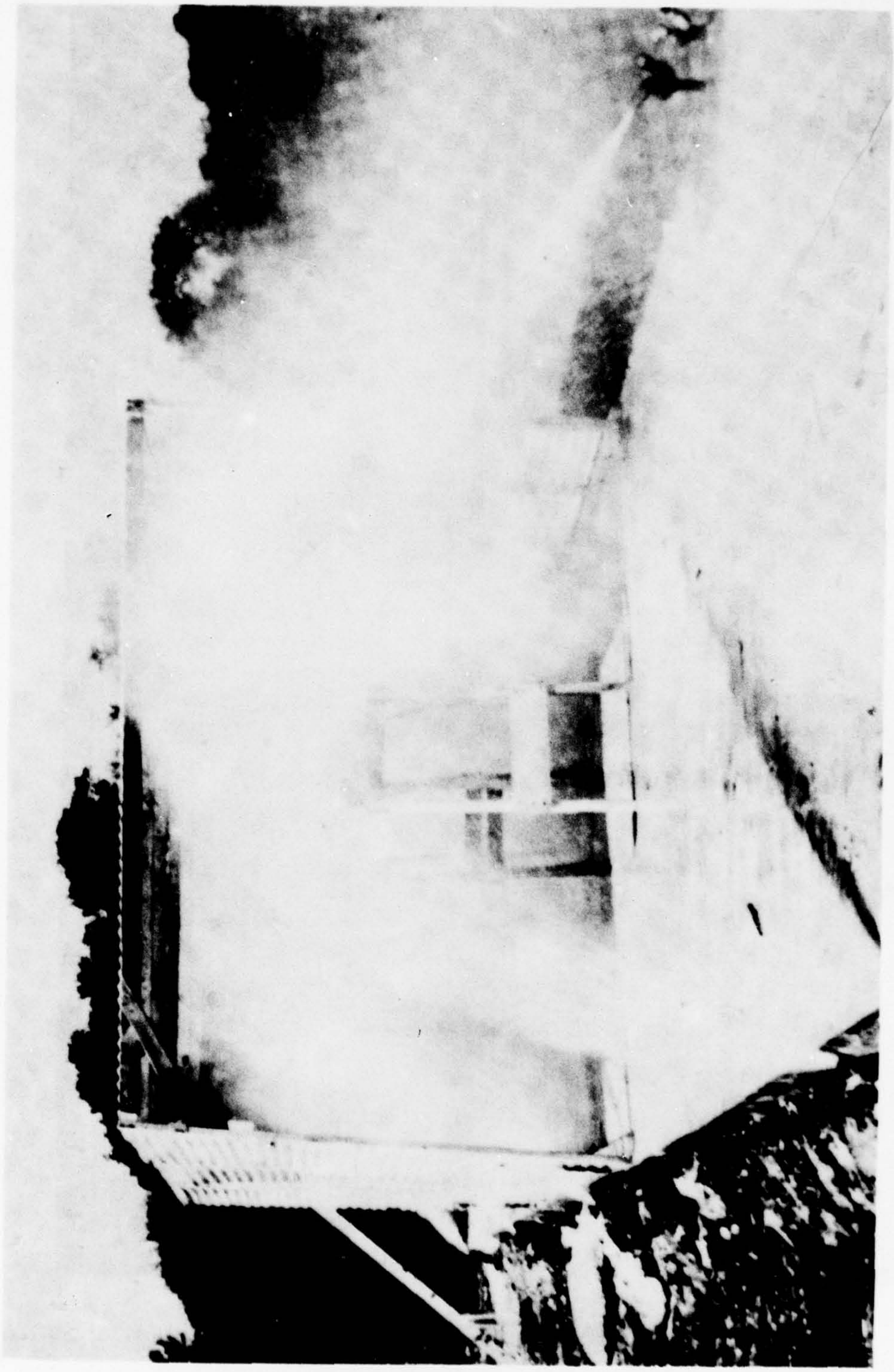

FIGURE 3. ACTIVATED "HARDENED" WATER DELUGE SYSTEM

In this application a UV detector (spectrum of 1850 to 2450 Å) was used to detect the fire, and the electrical signal from this detector was used to activate a solenoid valve which released the water through a dry-pipe system. In other applications to be discussed later, the signal from the detector was used to activate an explosive valve to release water to a wet-pipe system. These variations in the design of the deluge system will be discussed in detail as we progress through this review. The two boxes of Composition B are placed on a table, and the height of that table simulates the height of the conveyor line at LAP facilities.

After detonation of the donor box, (Figure 4), the acceptor box did not detonate, nor did it burn. The acceptor is seen in the center of the photo. The water deluge system has acted to extinguish any extraneous fires that have occurred.

Obviously, the total tunnel used for this test has been completely destroyed, however, in the real life situation, had this tunnel been 400-500 feet long, elements of that tunnel would still be left standing. The deluge system has not been damaged in any way by the blast and fragments generated during the detonation.

In another series of tests, a hardened water deluge system was designed and tested to protect a Serpentex conveyor line transporting loose Composition B or Cyclotol. Figure 5 illustrates the test setup where, should a fire or detonation occur in one of the Serpentex buckets, the water deluge system was capable of extinguishing extraneous fires up and down the adjacent Serpentex buckets.

The design of "hardened" deluge systems is currently being continued to examine the case of an explosion as it might occur in the 105 mm Melt-Pour Facility now being built at Lone Star Ammunition Plant. In these tests, the problem is to design a deluge system capable of sustaining the detonation within one of the four buildings which constitutes a total melt-pour facility. Another case would be

FIGURE 4. OPERATING NOZZLE SYSTEM FOLLOWING DETONATION OF DONOR BOX

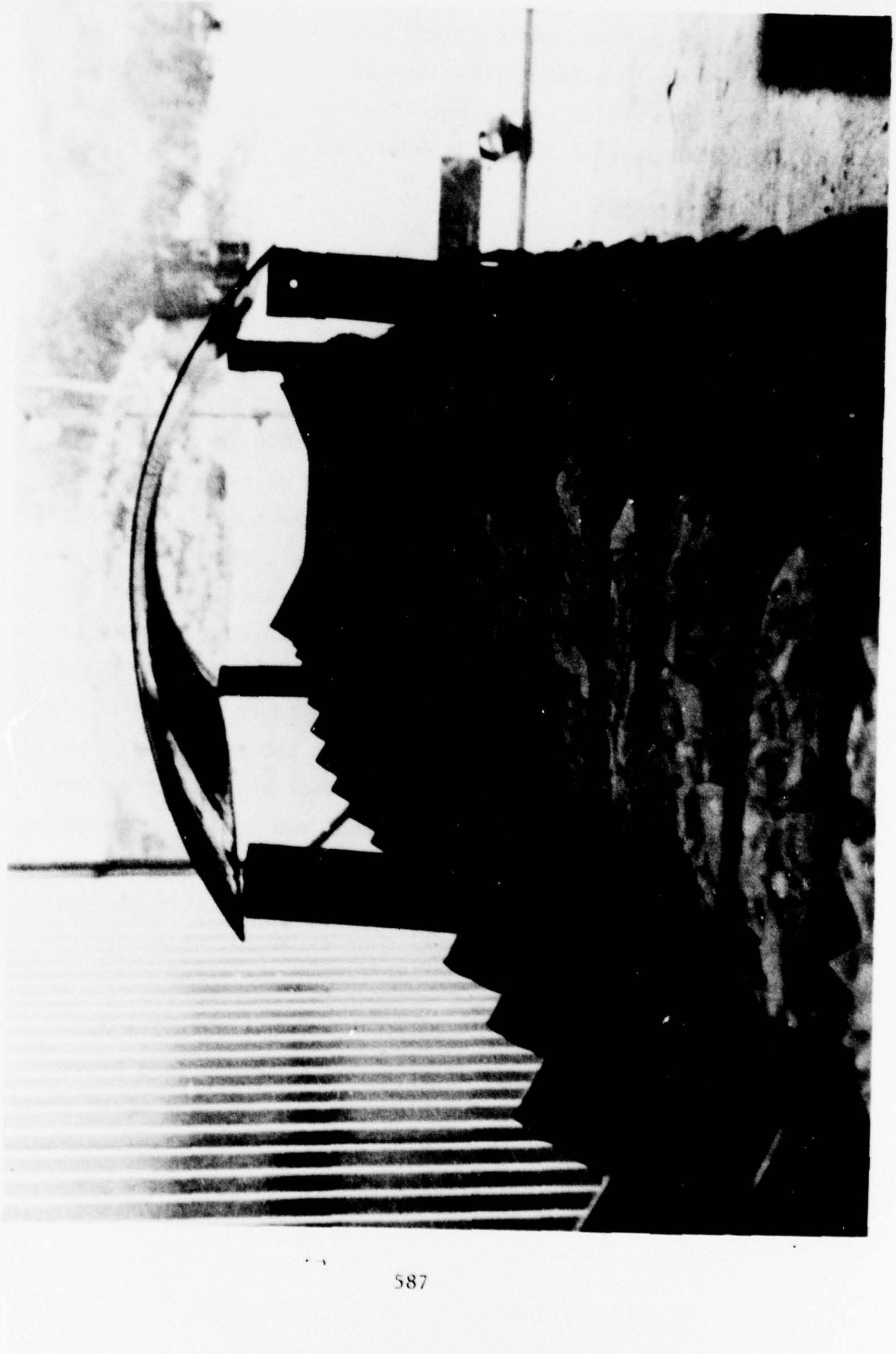

FIGURE 5. SERPENTEX CONVEYOR

the detonation and destruction of an entire building. For instance, in the receiving building at Lone Star, 92,000 lb of Composition B are handled at any single point in time and should this 92,000 lb detonate, the problem will be to prevent fire from propagating to the adjacent buildings as part of that melt-pour facility.

Conventional Deluge Systems

In Figure 6, one element of the 105 mm bag loading facility at the Indiana AAP is shown. Granular M1 propellant is loaded into bags, and the individual bags are then hung on a string much like a clothesline, seven bags constituting the full 105 mm charge. At Indiana, the M1 propellant is unloaded at a receiving dock and placed in a 1,000 lb hopper. This hopper, when loaded with 1,000 lb of M1 propellant has a depth of 43 inches. This height is in excess of the 18-in. height allowed by AMC385-100 Safety Manual. If the height exceeds 18 inches, the facility is classified Class 1.1, however, should these tests prove successful, the facility can be reclassified as Class 1.3 (only a fire hazard). The first, and probably the most important concern of the test, was to answer the question: "Does a detonation occur? Will a deflagration, which originally started as a fire in the bottom of the hopper transcend into a full-scale detonation of the material? Can a water deluge system control the fire and prevent a full detonation?" To answer these questions a water deluge system was designed consisting of two main water lines, each of which were 2.5-in. in diameter, fed two nozzles on each line. These nozzles, at a line pressure of 65 psi, yielded 10 gallons per minute per square foot water coverage, and can be seen in Figure 7.

The deluge system used in this application consisted of a UV detector whose output signal fired a detonator contained in a Primac valve. The detonator severs a restraining pin and the line water pressure pushes the valve open, thus releasing water to a wet-line system. Prior to activation of the Primac release valve, the lines are precharged with water to the nozzles, and a rupture disc contained in each

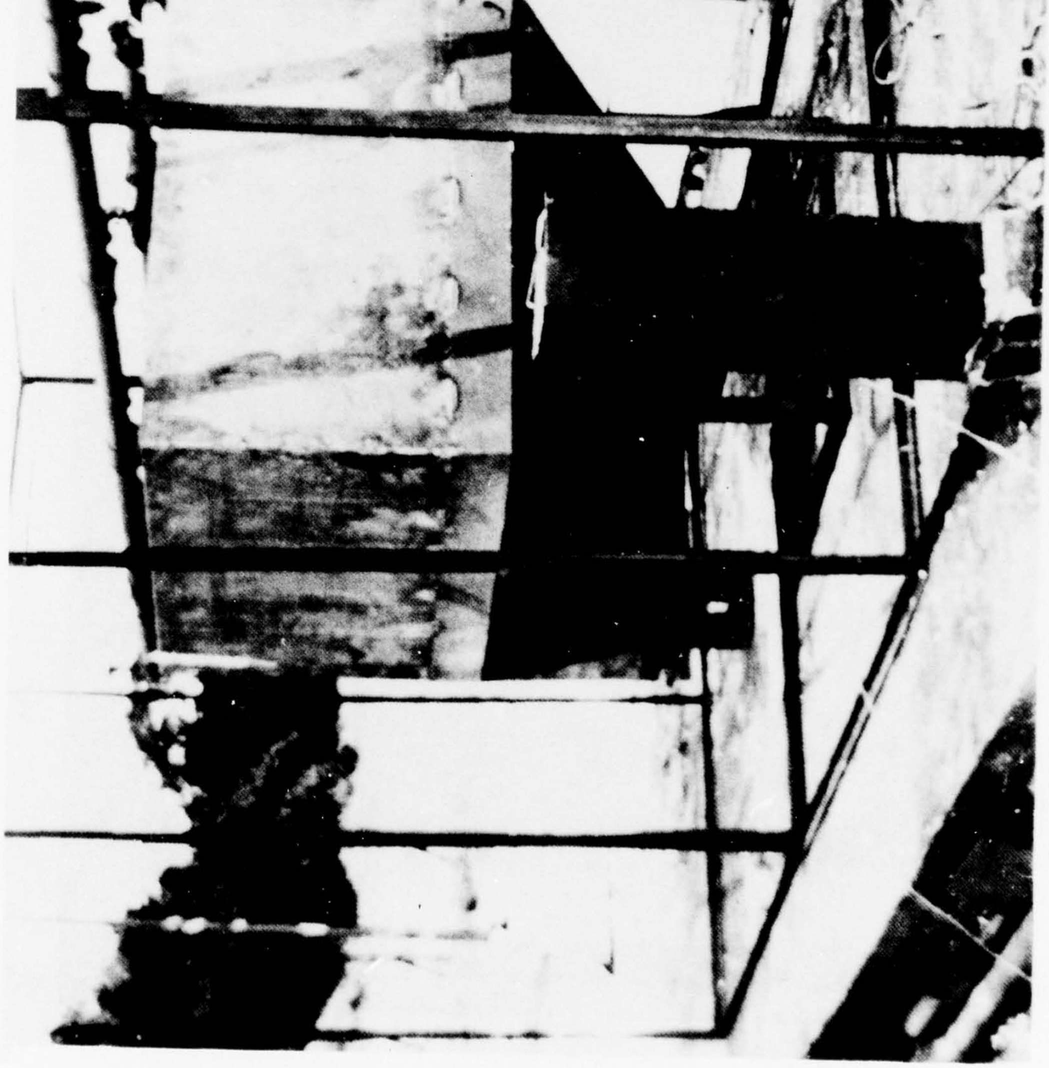

FIGURE 6. 1000 LB RECEIVING HOPPER AT INDIANA

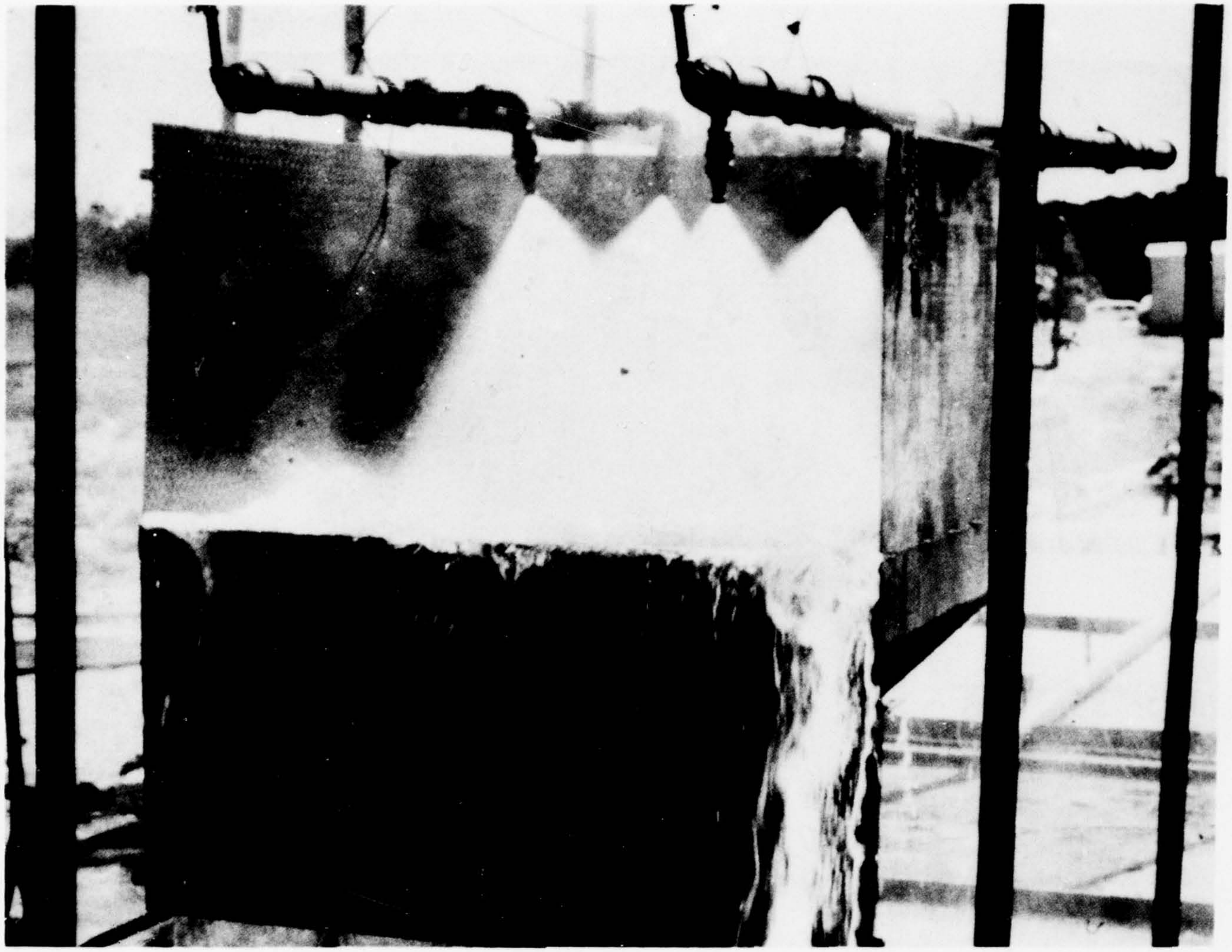

FIGURE 7. ACTIVATED "CONVENTIONAL" DELUGE SYSTEM FOR HOPPER

individual nozzle restrains the water until the full line pressure causes the disc to rupture.

Figure 8 shows the fire as it occurred. To examine the worst possible case, the propellant was ignited at the bottom of the hopper and all of the material being ejected from the hopper is the result of gas pressure generated near the point of ignition. For these tests, we did not concern ourselves with the material that is being ejected out of the hopper since this material, in the real plant environment, would have fallen down on a concrete non-flammable roof. We are only concerned with the condition of the hopper. Does a detonation occur? Does the hopper rupture? Is the hopper deformed by the heat? and so forth. Obviously, it can be seen that the hopper is still intact, Also visible in the photo is an indicator nozzle showing that the water is on; the fire is being quenched and subsequently it will be put out. While the fire was still burning, it was quenched by the water to a point where the deflagration was less intense. Consequently, the hopper was not damaged and for the most part, the tests yielded recovered propellant in quantities 25-50% of the original propellant mass.

Figure 9 shows the next process at the Indiana Army Ammunition Plant. Loose propellant has been loaded into bags and these individual bags travel along a conveyor line to the next point in the processing operations. The concern here is not whether a fire can be extinguished per se, because certainly with a line of single bags, that does not appear to be a great problem. The real problem came from the consideration of water adequacy at the Indiana plant. These lines collectively at Indiana amount to many hundreds of linear feet, and consequently, should a fire occur, to have all of these nozzles erupt at one time would cause a severe drop in the line pressure and also a severe water adequacy problem. So the intent of these tests was to design a deluge system which would extinguish a fire in one of these line conveyors with the absolute minimum amount of water coverage. In this particular instance, it was demonstrated that fires could be extinguished within a single

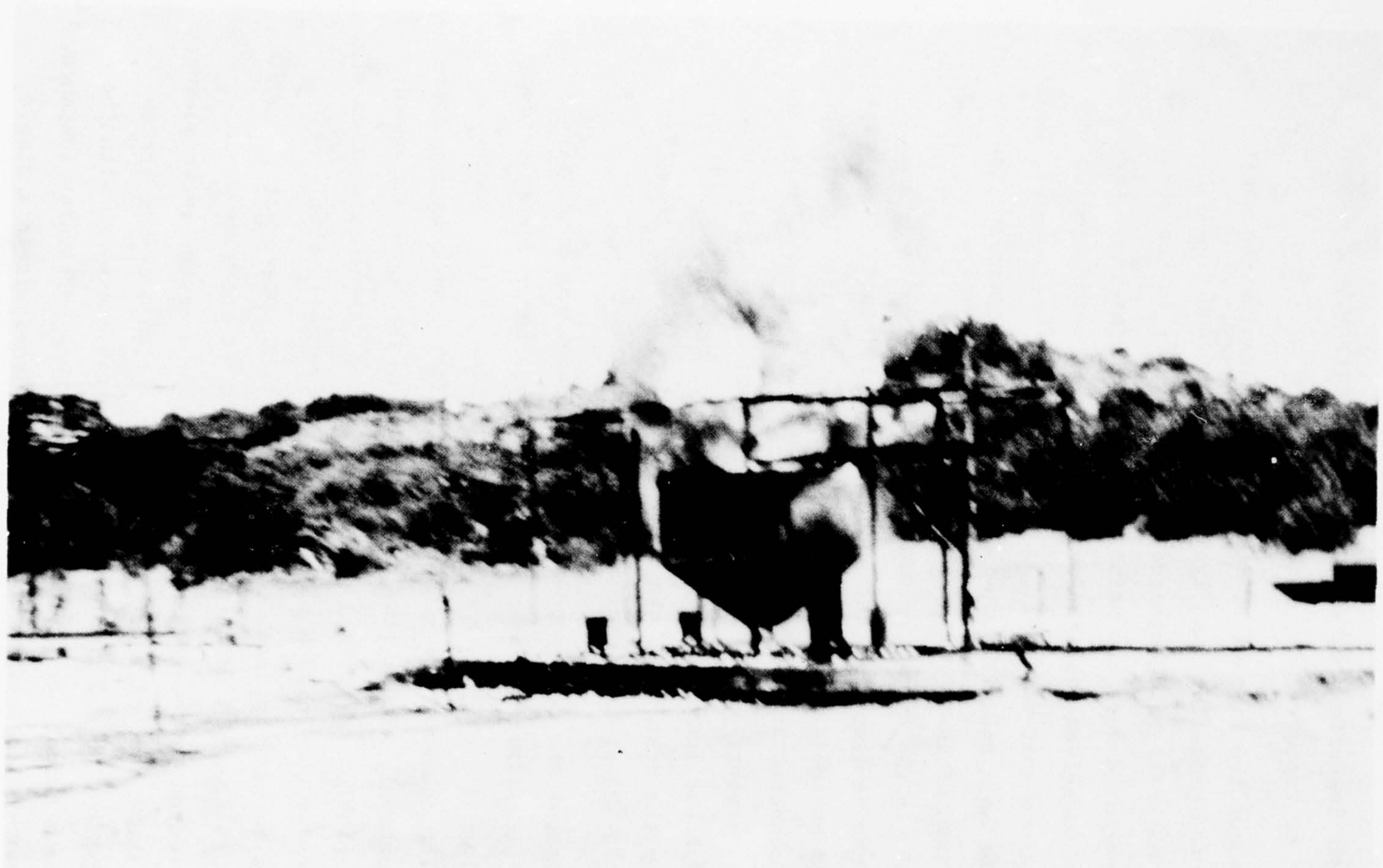

FIGURE 8. M-1 PROPELLANT FIRE IN 1000 LB HOPPER

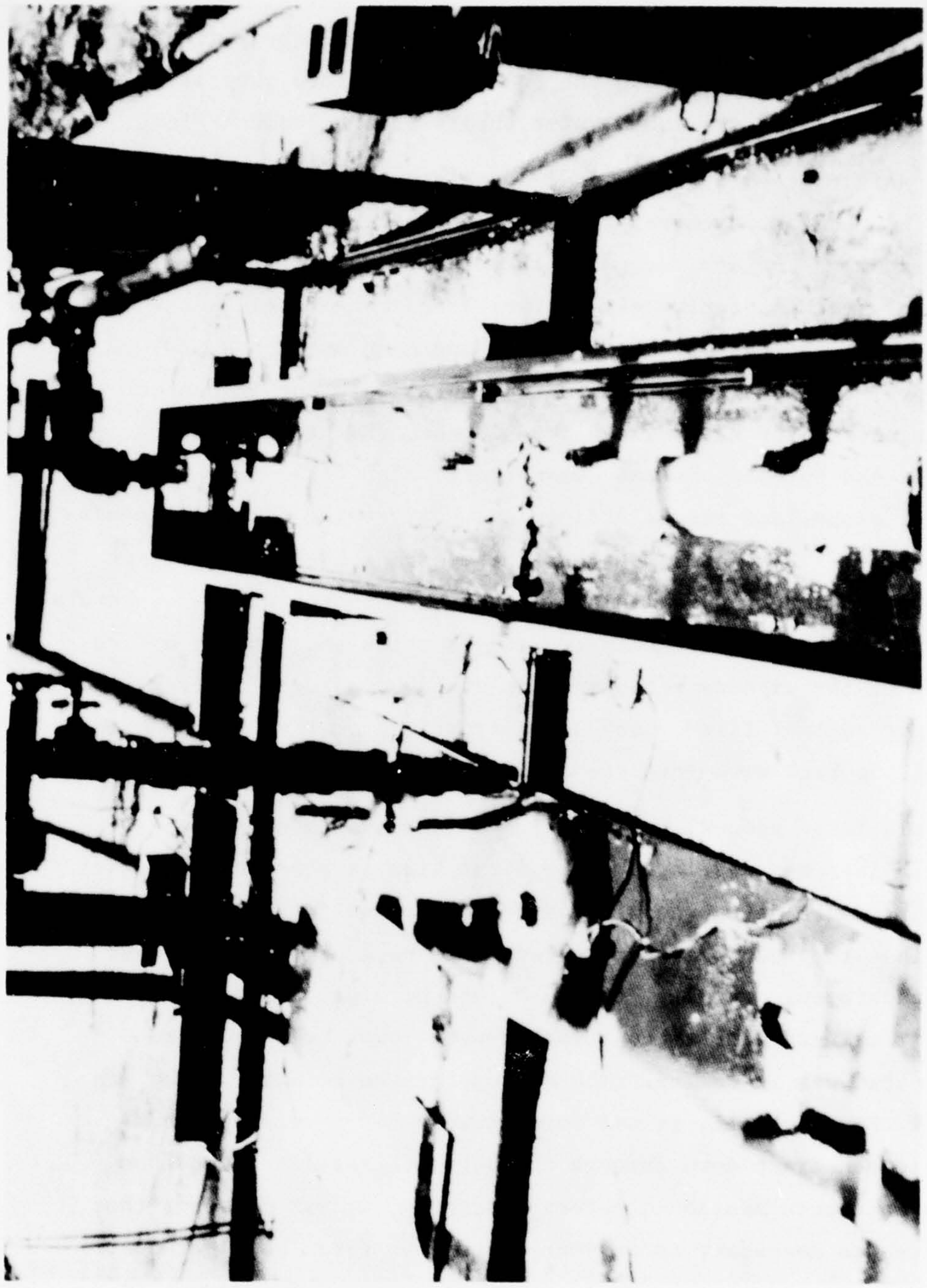

FIGURE 9. FIRE EXTINGUISHMENT ON LINE CONVEYOR AFTER BURYING ONLY ONE BAG

bag from the point of ignition. This could be accomplished with as little as 0.15 gallons per minute per square foot. This quantity was in perspective with the available water supply at the Indiana Plant.

In the next processing step, individual bags moving down a line conveyor are dumped into accumulators as seen in Figure 10. In the accumulator room in Indiana, seven of these accumulators are parallel to one another, each approximately 70 feet long. The total bags contained in that room at any one time can approach as much as 70,000 lb. Therefore, should a detonation or deflagration occur in one of these accumulators, the results could be catastrophic to the entire plant. First and foremost it was demonstrated that fires in these quantities of propellant can be extinguished before the fire transcends into a detonation. The donor on the right contains bagged propellant 16-in. deep simulating the real-plant situation. In the witness accumulator on the left, the bags are only two layers thick and, should a fire occur in one of the witness acceptors, it would have to be ignited from the top as a result of fire brands being erupted from the donor, deflected off the roof and back down into the acceptor accumulator.

To battle large accumulator fires, a deluge system consisting of two parallel lines was developed. The first line is a series of cut-off or high pressure deluge nozzles designed to have force behind the water such that they can penetrate through the bags of propellant and prevent an underburn. Parallel to the deluge nozzles, a series of area coverage nozzles very similar to a more conventional overhead fire sprinkler system was installed. The reason for the parallel lines was severalfold. First of all, it was evident very heavy water pressure was needed to penetrate down through the bags of propellant and thus prevent the underburn mentioned above. Secondly, it was apparent that area coverage was necessary to prevent extraneous fires as might occur from fire brands being thrown around the total accumulator room. It would be impossible within the water adequacy and water pressure limits at Indiana to have deluge nozzles activated throughout the entire room.

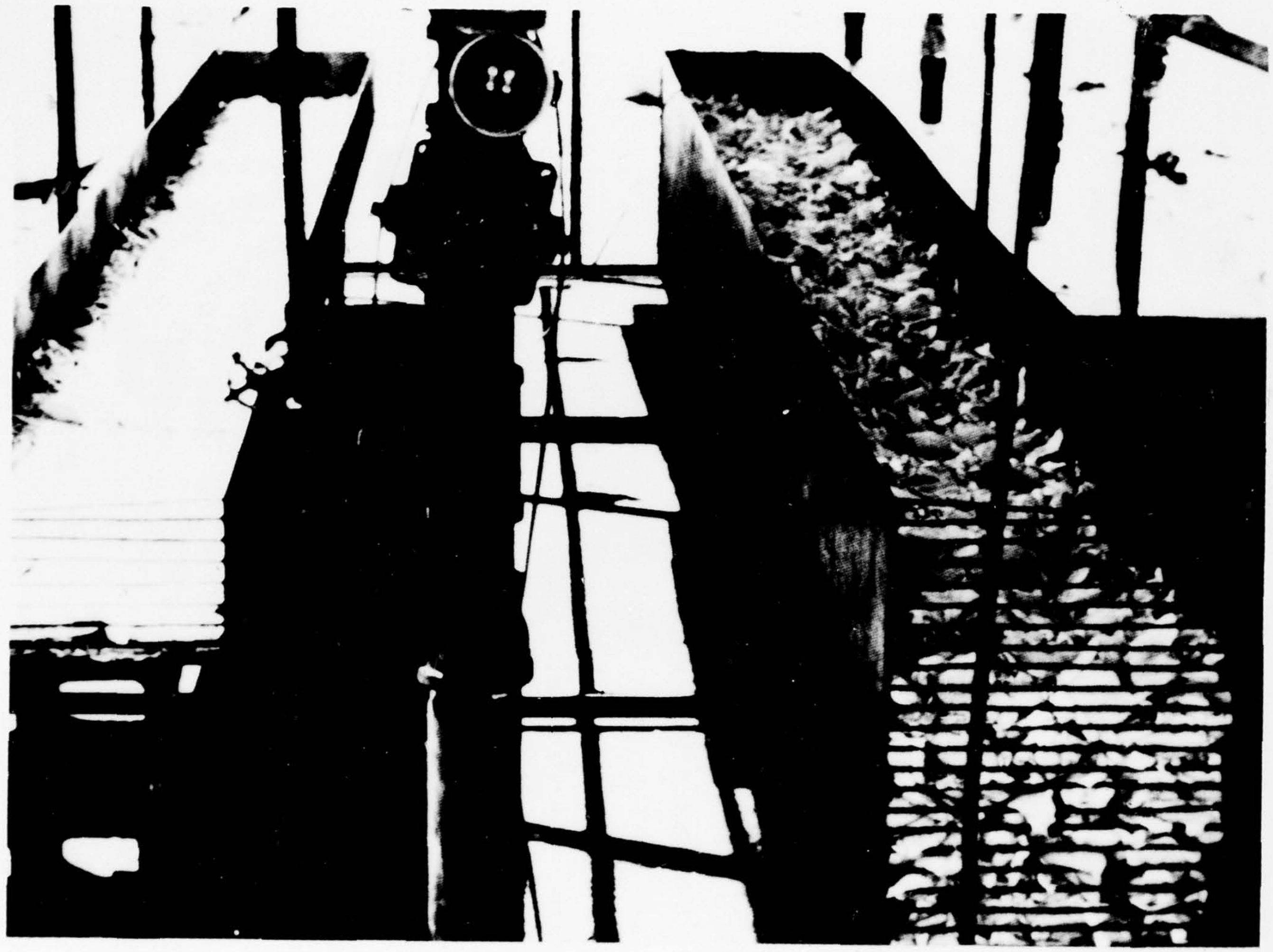

FIGURE 10. BAGGED M-1 PROPELLANT IN SIMULATED ACCUMULATORS

Consequently, through the design of a preferential detection system, a detector would sense a fire in the donor accumulator where the fire originated and the deluge nozzles over that accumulator, and only that accumulator, would be activated. Through the same preferential electronic system, we could actuate the area coverage nozzles throughout the entire room thus wetting down all of the adjacent or witness accumulators. Using this means of preferential water application, it was possible to design a system for this large room at Indiana that could accomplish both the attack of a fire down through a 16-in. depth of propellant and at the same time take care of the extraneous fires as they might occur throughout the rest of the room.

Figure 11 shows this fire in all its fury, and these flames reached 100 feet in the air in many cases. Here the material raining down on the floor surrounding the accumulators is of vital concern to us because, in contrast to the hopper test, all of this material would have been deflected off the roof and back down into the adjacent accumulators. It was possible, however, to control those surface burn fires as they started. This is demonstrated in Figure 12.

The white bags projecting out of the end of the accumulator indicate that the fire did not propagate to this point nor was there any underburn of that fire. The deluge nozzles did indeed penetrate and stop the fire. Some surface burning is seen; however, this could easily be controlled by subsequent nozzles further down the line. The test section of accumulator is only 15 feet long out of a real in-plant situation where these accumulators are up to 70 feet long yet, it was demonstrated that the fire could be extinguished within 8 ft. of the point of ignition.

Another facet of the deluge program was undertaken for the Radford Ammunition Plant. Their concern was the possible occurrence of a fire in one of their closed and partially sealed conveyor lines connecting several process points within the plant. Figure 13 shows a section taken from one of those lines. This conveyor is an airveyor,

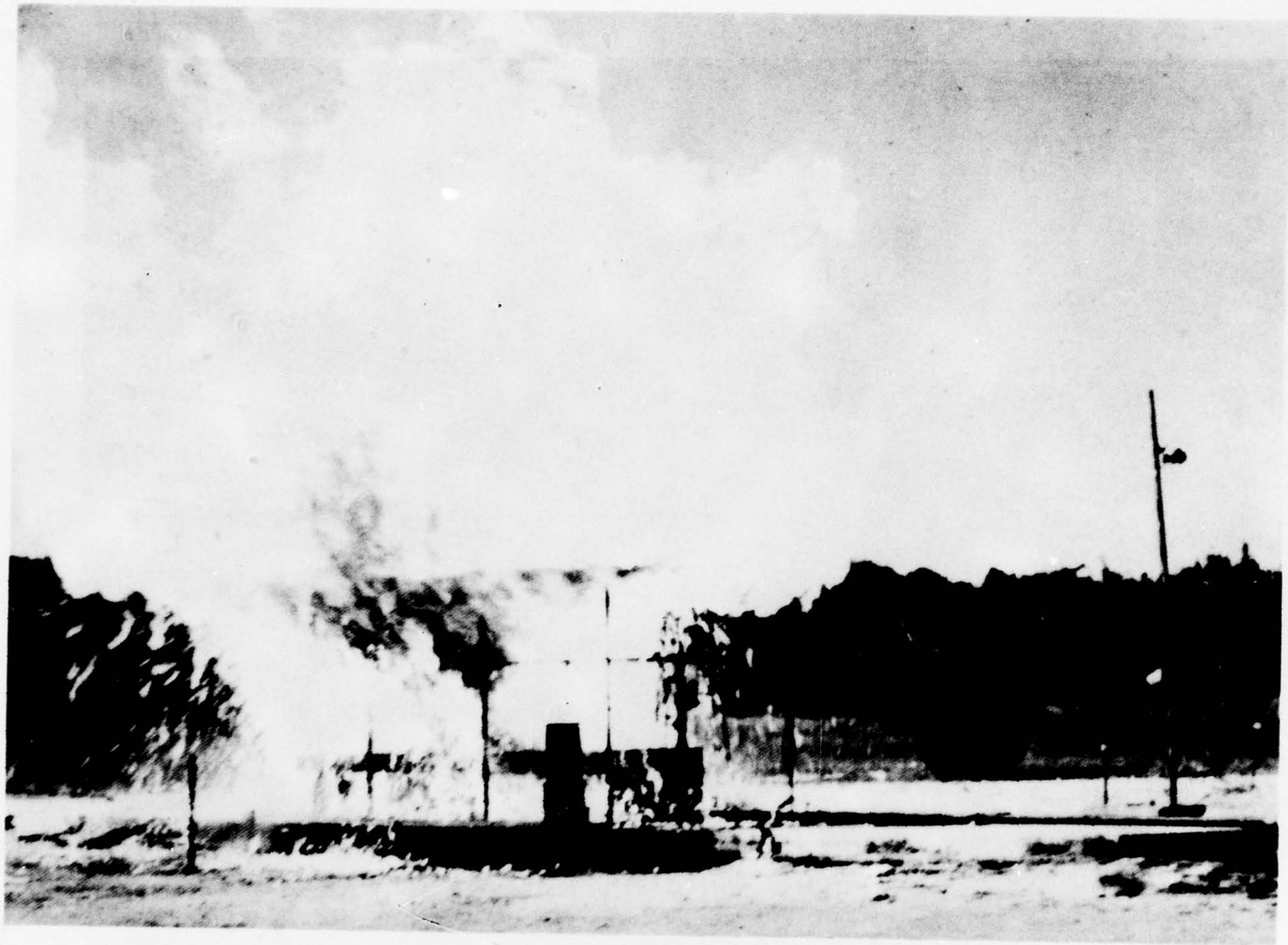

FIGURE 11. ACCUMULATOR FIRE 10 SECONDS AFTER IGNITION, WATER DELUGE ACTIVATED

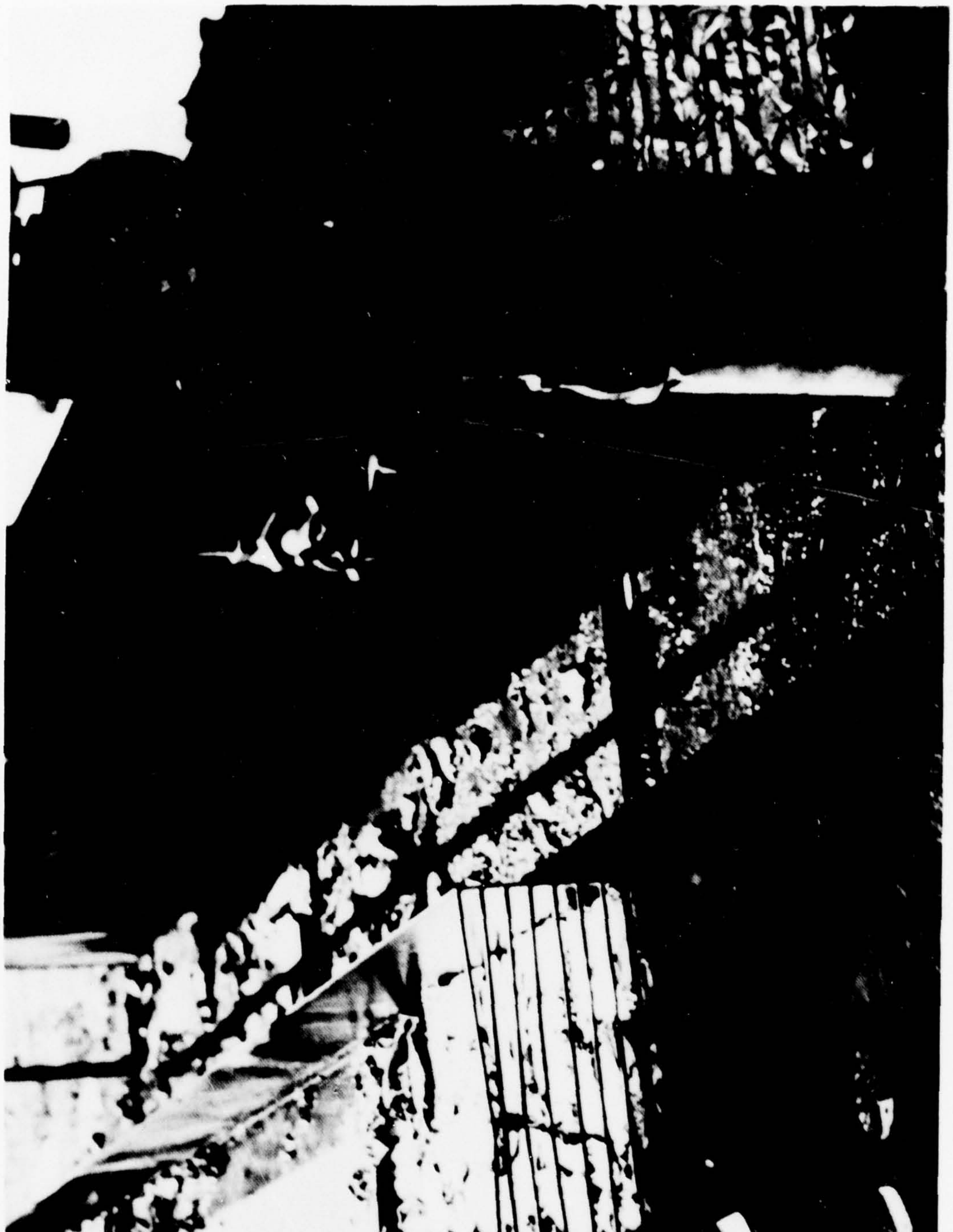

FIGURE 12. RESIDUE FOLLOWING EXTINGUISHMENT OF FIRE BY WATER DELUGE SYSTEM

FIGURE 13. SIMULATED RADFORD AAP AIRVEYOR FOR LOOSE M-1 PROPELLANT

meaning that the material is conveyed by air jets along this particular conveyor. The test section is 13 feet long, 6-in. high and 12-in. wide with loose M1 propellant being conveyed. In the real-plant situation, there would have been an input chute on one end and at the far end would be a drop-out chute in the bottom which moves the propellant onto the next stage of the process. Again, a deluge system was designed utilizing, in this particular case four nozzles, and the detectors are placed at the far end of the conveyor to look down this entire length of the conveyor line. For this application, both UV and IR detectors were used to compare the response time of these detectors to the same flame source. Through an "either-or" electronics circuit, the first detector which sensed the fire would activate a Primac valve thus releasing water to the deluge system. Since the Radford AAP commonly has available a minimum of 90 psi mainline water pressure, this line pressure was used in the test. 100° divergent nozzles were used within the close confines of the Radford conveyor and the water coverage within the conveyor was 7.4 GPM per square foot.

Figure 14 shows the residue, and in this particular view, the recovery was in the neighborhood of 90%. A point to be made here is that through these tests it was clearly demonstrated that a fire can be extinguished in these conveyor lines and it was also very apparent that the fire could be controlled before it would propagate very far down a conveyor regardless of the total length of that conveyor. Consequently, after careful assessment of all of the test results, it was recommended that Radford eliminate the fire gates that originally had been planned for installation in the plant. These fire gates, being very massive, complex, and also very expensive devices were, therefore, eliminated thus saving the Army close to one million dollars.

These evaluations of the Radford conveyor deluge system resulted in another important discovery.due to the placement of the detectors at the extreme end of the conveyor. Should a fire occur at the far end of the conveyor, the detectors would have to "see" the fire

FIGURE 14. 90% RECOVERY OF PROPELLANT FOLLOWING FIRE AND WATER DELUGE SYSTEM

from a distance of at least 13 feet. It was found that the IR detectors currently being used at the Radford Plant were incapable of observing a fire at that distance. It was also found that the solvent vapors, i.e., alcohol and ether, emanating from the solvent wet propellant, would also obscure the view of the detectors. The IR detectors were particularly sensitive to this atmospheric contaminant, thus it was demonstrated that extreme care should be used in selecting a particular detector for use in a plant with known atmospheric contaminants and with physical constraints on the location of these detectors.

Moving on now to the next series of tests that the program addressed, Figure 15 shows a conveyor line transporting boxes of bagged igniters. These igniters come in a variety of forms, and the following have been tested: the 5 oz. Black Powder igniter, the 3 oz. CBI or clean burning igniter, as well as the center core igniters. All three of these igniters find application to the 155 mm and 8-in. gun and the important concern for these tests was to determine the safety classification of these boxed igniters. Obviously, if it can be demonstrated that these boxed igniters are Class 1.3 fire hazards and not a Class 1.1 explosive hazard, the savings in cost in plant construction will be significant. The particular test shown here in this view is the test of the black powder igniters on two conveyor lines, one on top of the other. In the real plant situation there are six of these conveyors, one on top of the other. SwRI was challenged to extinguish a fire should one occur in these bag igniter conveyor lines by using a water deluge emanating from only one side of the building. This was obviously a plant construction limitation, and consequently you see only a single water deluge line placed on the back side of this conveyor. For the purposes of this test only three nozzles were used, and these nozzles, because of their 50° spray angle, were able to cover the top of these boxes as well as to project water down into the space between the boxes.

Figure 16 shows the very rapid burn of black powder propellant. As the powder burns, there is an increase in pressure and a big whoosh as the material is consumed.

FIGURE 15. TOTE BINS OF BLACK POWDER IGNITOR ON TWO SIMULATED CONVEYOR LINES

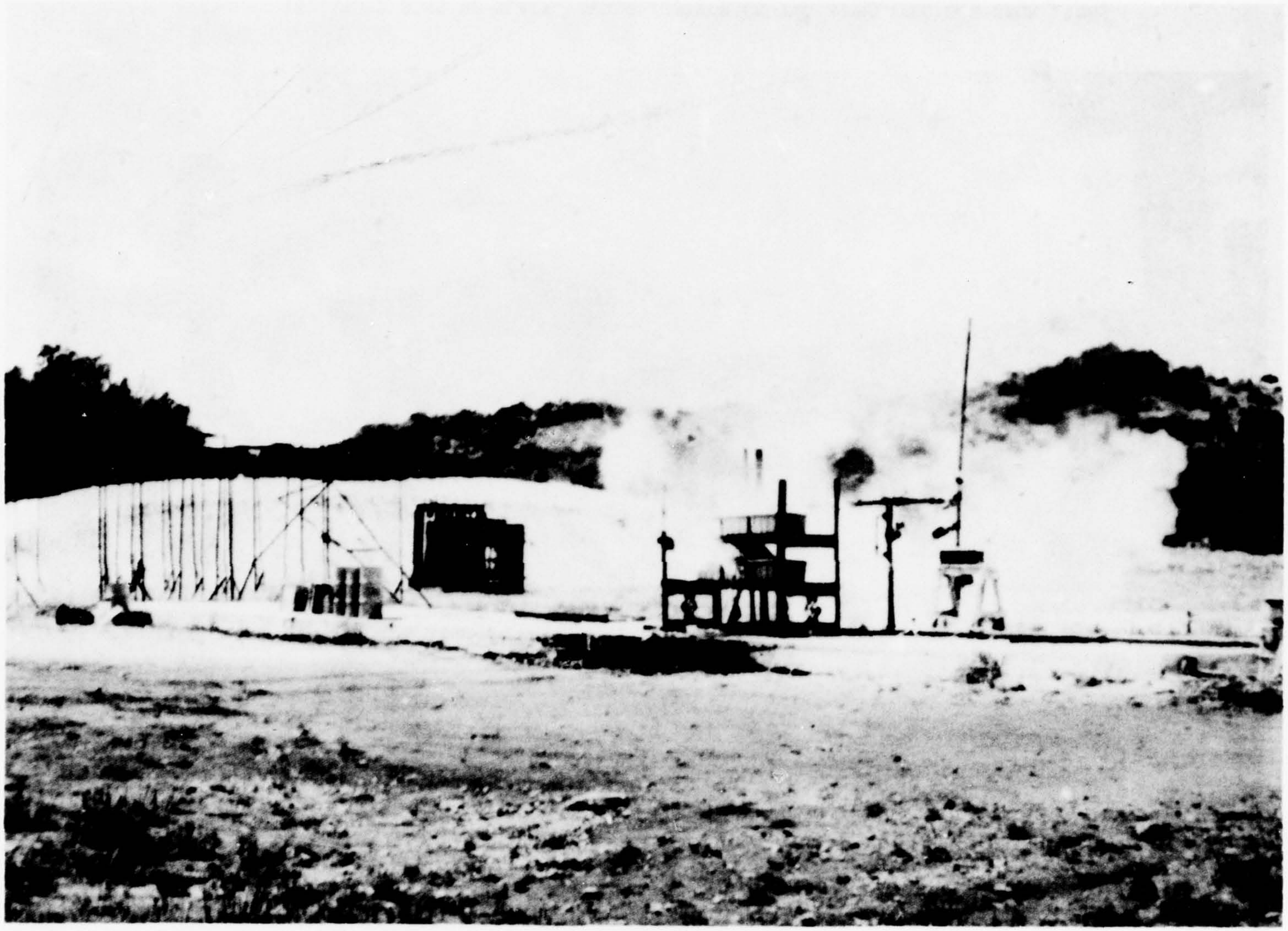

FIGURE 16. WATER DELUGE EXTINGUISHING EXTRANEOUS FIRES

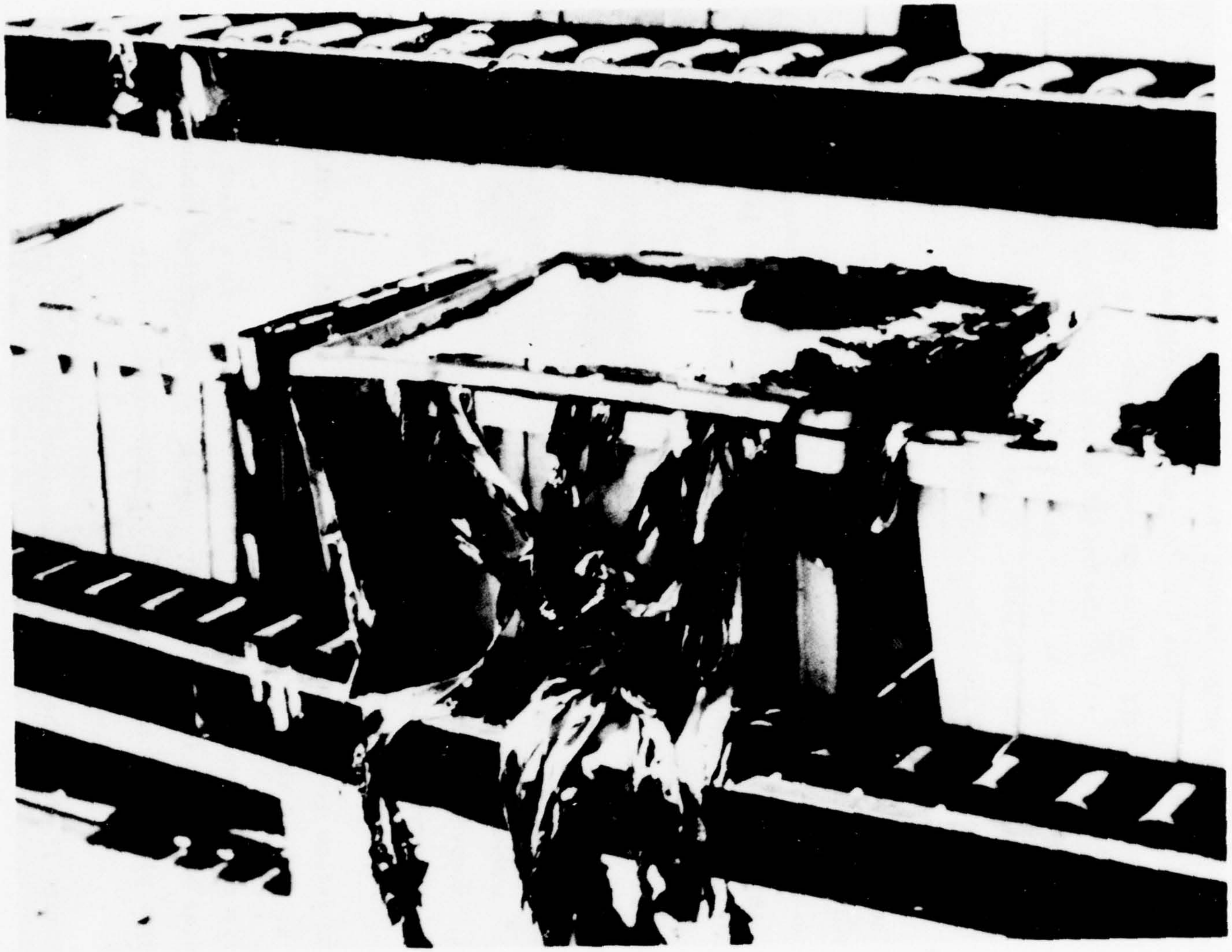

FIGURE 17. CLOSE-UP VIEW OF TOTE BINS AFTER FIRE EXTINGUISHMENT

Figure 17 shows the aftermath of the fire. Here, very clearly, one can see the bags of propellant that have been ejected out of the box. The lid of the box has been bulged and again the charred material from the bags did indeed land on neighboring boxes, but were extinguished by the water deluge. All of the bagged material hanging out of the box was also extinguished by the water deluge system and in this particular case, two conclusions can be made. First, there was no detonation of the material in any of the boxes, and secondly, extraneous fires can indeed be extinguished.

The next series of tests in the water deluge development program involved the extinguishment of fires as they may occur in the lead azide processing plant at the Lone Star, Iowa and Kansas Army Ammunition Plants. The concern here was not the burning of lead azide because lead azide does not burn, but rather it will detonate. So the concern lies with the fire as it might occur in the alcohol, or in the alcohol soaked sawdust which surrounds the lead azide material. In the receiving/processing of lead azide at the plant, four distinct steps are followed:

1. Unpacking from the drums. Lead azide is surrounded with sawdust and alcohol.
2. Removal of putty consistency lead azide from the bag.
3. Placement of lead azide into drying tube.
4. Placement of drying tube into transport buggy.

A water deluge system was designed and tested to control and extinguish fires in each of these process steps.

Figure 18 shows a sample of lead azide contained in a black gabardine bag which in turn is surrounded by alcohol-soaked sawdust. The white plastic container is simply a convenient container for use in the test.

Figure 19 shows the container placed on a pedestal underneath our deluge nozzle and the mechanical switch which was used to indicate the water-on condition. An electric match is used to ignite the alcohol

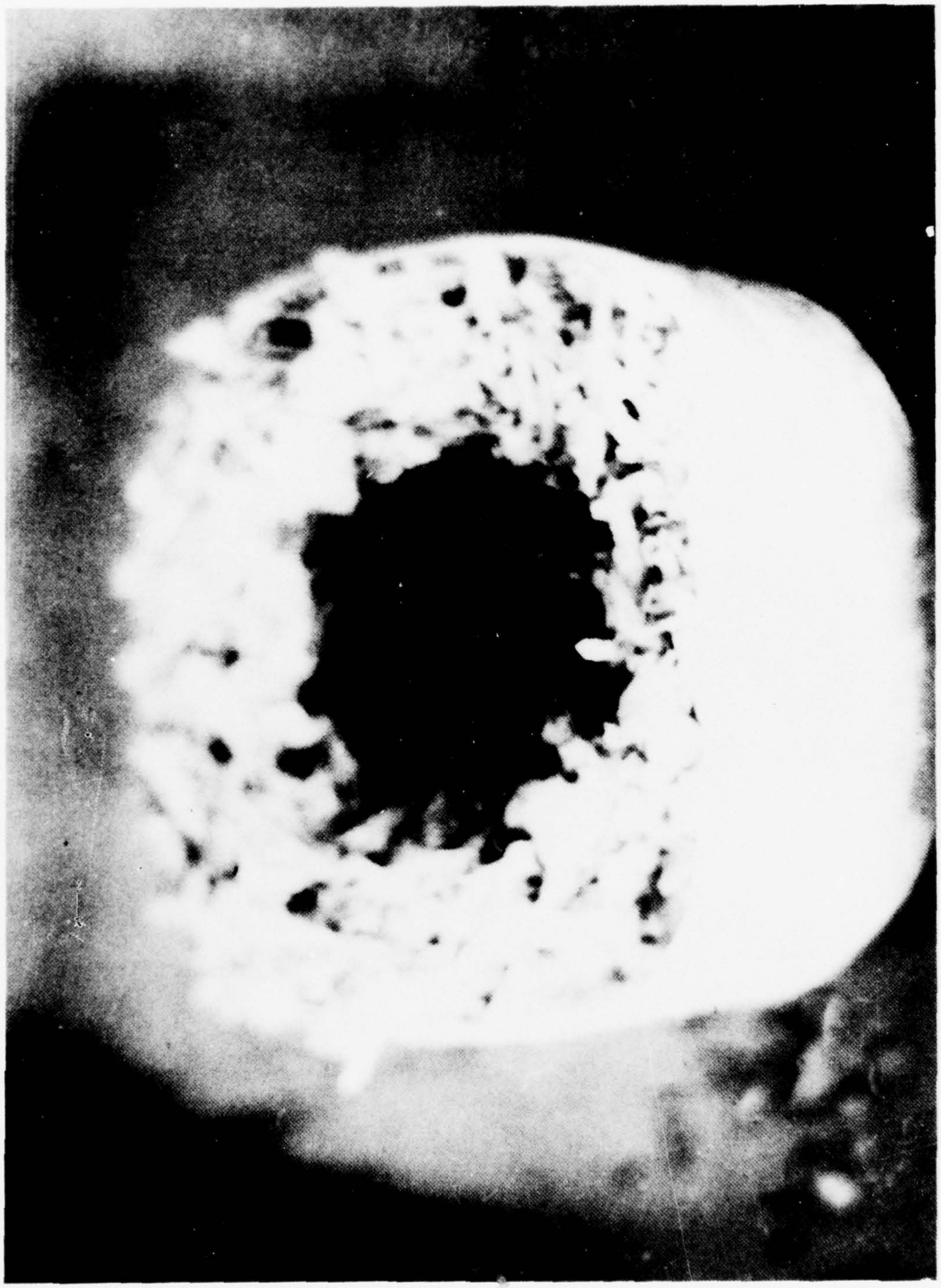

FIGURE 18. BLACK BAG CONTAINING LEAD AZIDE SURROUNDED BY ALCOHOL SOAKED SAWDUST

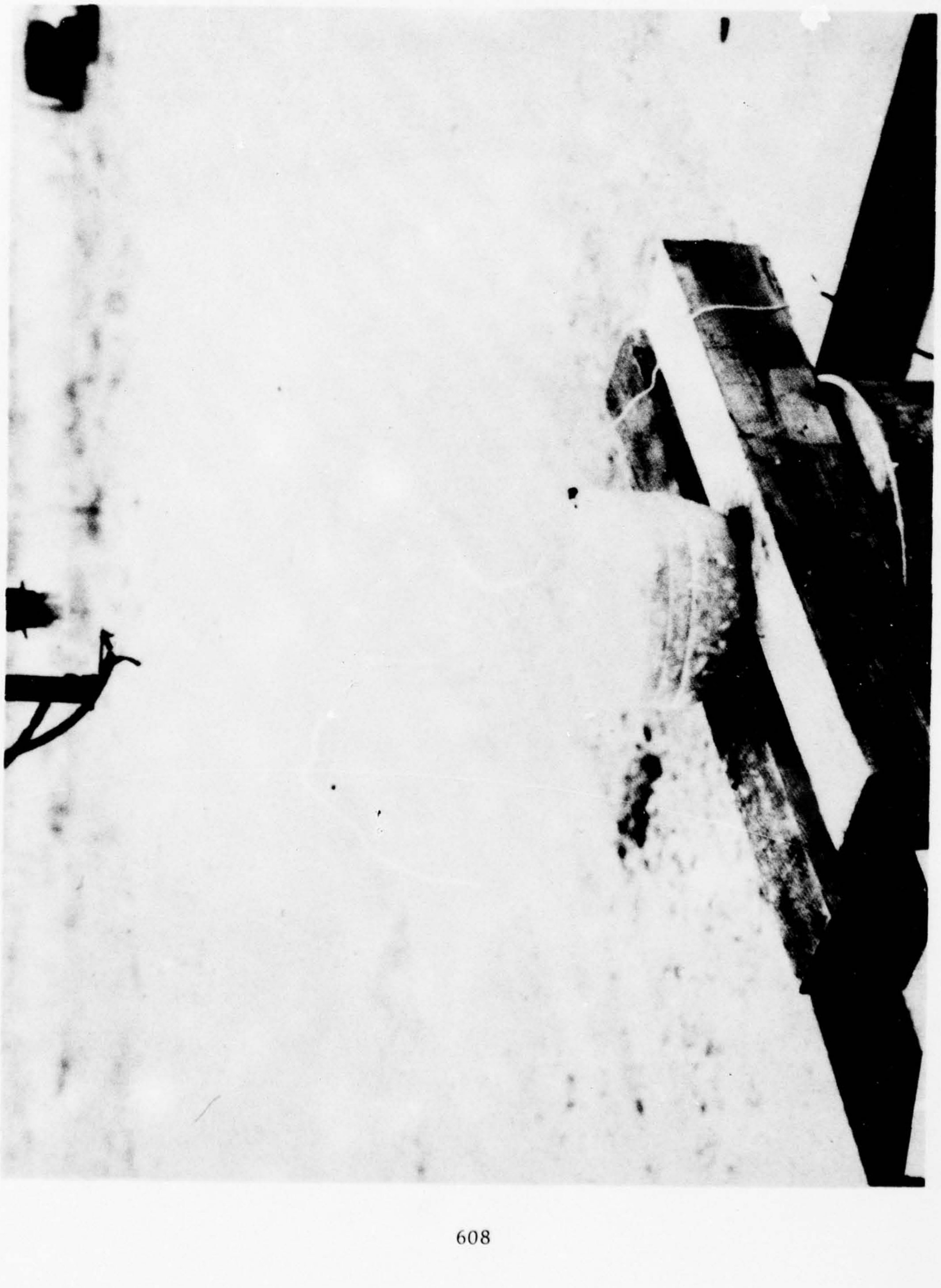

FIGURE 19. ALCOHOL/SAWDUST LEAD AZIDE UNDER DELUGE NOZZLE PRIOR TO TEST

vapors immediately over the wet sawdust, and the water nozzle is used to extinguish the fire.

Figure 20 shows the process wherein the azide is kneaded into a putty consistency prior to removal from the bag and placement into the drying tube. The kneaded material is placed in a pan and is then placed into a container bucket which was used to confine the material should it be pushed around by the water deluge. One of the major concerns at the Lone Star Plant was, that should a deluge system be capable of extinguishing a fire, the force of the water might literally throw this lead azide all over the room in which these particular operations are being carried out. Even if a detonation did not occur, the cleanup process might be more hazardous than should a fire occur and burn to eventual detonation. Consequently, a vital concern here was to attempt at least to keep the lead azide constrained so that the cleanup problem would not be severe. In a series of tests, it was demonstrated that those fires could be extinguished by a deluge system applying 0.33 GPM per square foot of water into the holding vessel.

Figure 21 shows the next series of tests wherein the putty consistency lead azide is placed in a drying tube and the drying tube is then immersed in alcohol. Here, two lbs of lead azide has been placed in a drying tube under a 0.25-in. head of alcohol.

Figure 22 shows the set-up just prior to test. The stainless steel kettle containing the drying tube, again is placed under the deluge nozzle and the water-on mechanical indicator switch can be clearly seen. Again, the height of the nozzle here is significant only to control the rate of application of water into the stainless steel kettle at 0.33 GPM/ft^2. For these particular tests, the fire was extinguished before the kettle was even filled with water.

The tests proved a rather significant result and Figure 23 shows that the application of the water into that kettle was so gentle that it did not disturb the lead azide nor in any way excite it to a point

FIGURE 20. FIRE IN PUTTY CONSISTENCY LEAD AZIDE EXTINGUISHED--NO DISPLACEMENT OF LEAD AZIDE

FIGURE 21. LEAD AZIDE IN DRYING TUBE IMMERSED IN ALCOHOL

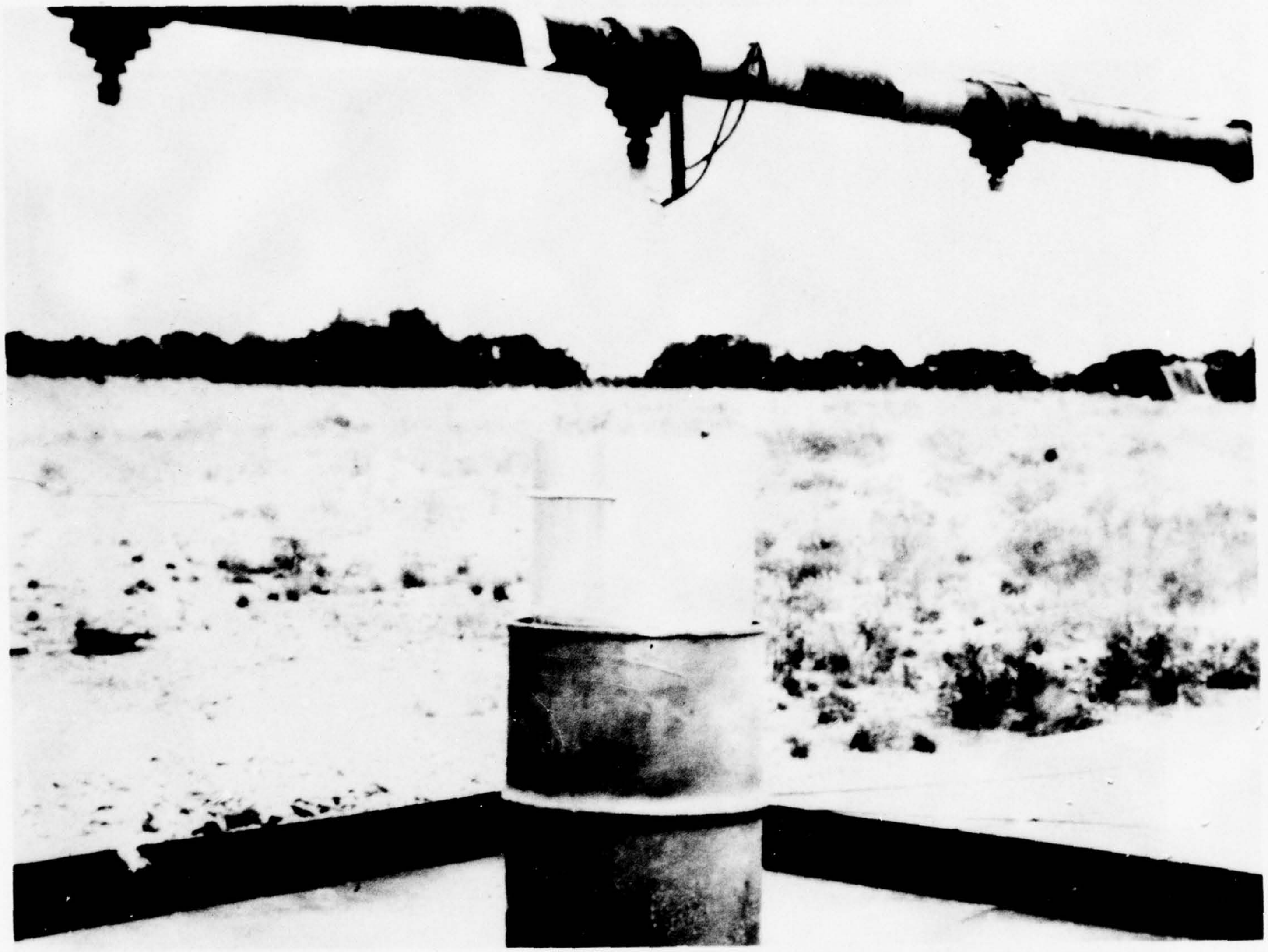

FIGURE 22. LEAD AZIDE IN DRYING TUBE UNDER DELUGE NOZZLE PRIOR TO TEST

FIGURE 23. LEAD AZIDE AFTER EXTINGUISHMENT OF FIRE. NOTE THAT NO DISPLACEMENT OF LEAD AZIDE OCCURRED.

of detonation. Consequently, it can be concluded from these tests that, without question, a fire in lead azide can be extinguished without disturbing the material to a point where it's been dispersed throughout the room and would pose a serious cleanup problem.

Summary

Through the course of this presentation an attempt was made to set forth the reasons for which the projects were conducted and to demonstrate the applicability of the work. Figure 24 reiterates each of the test programs, and a list of available references follows. Significantly, the user agencies, the respective Army Ammunition Plants, have seen fit to send representatives to witness the tests to receive interim briefings on the test results and to carry back with them sufficient information to enable the test results to be immediately incorporated into the building design for the modernized ammunition plants. The implementation of the test results can be clearly demonstrated by considering the case of the elimination of the fire gates at the Radford Plant, and redesign of the detector locations also at the Radford Plant. The modification of the building design in the Indiana accumulator rooms to satisfy the requirements of a Class 1.3 as opposed to a Class 1.1 hazard, and the initiation of plans to install a water deluge system in the lead azide handling facilities at Lone Star, Kansas, and Iowa AAP's are also results of this program. These are but a few of the examples of the immediate implementation of the test results. The cost reductions or cost savings to the government certainly far exceed the development program costs.

FIGURE 24

WATER DELUGE APPLICATION IN MUNITION PLANTS

PROGRAM	AMMUNITION PLANT	RESULT
Comp B Conveyor Line	Lone Star	Fires Prevented
Serpentex Conveyor	Lone Star	Fires Prevented
M-1 Propellant Conveyor	Radford	Firegates Eliminated Detectors Changed
M-1 Receiving Hopper	Indiana	Fire Extinguished @ 10 GPM/FT^2
M-1 Single Bag Conveyor	Indiana	Fire Extinguished @ 0.2 GPM/FT^2
M-1 Accumulators	Indiana	Fire Stopped Within 8'
Lead Azide Unpacking	Lone Star, Milan, Kansas Iowa	Fire Extinguished And Cleanup Eliminated
Bagged Igniters	Indiana	Fires Extinguished

References

1. J. W. Gehring, R. N. Rindner, W. Seals, "Design of a Deluge System to Extinguish Lead Azide Fires, ARLCD-CR-78014, December 1977.

2. J. W. Gehring, R. N. Rindner, W. Seals, "Development of a Water Deluge System to Extinguish M-1 Propellant Fires, ARLCD-CR-78024, January, 1978.

3. J. W. Gehring, R. N. Rindner, W. Seals, "Design of a Water Deluge to Extinguish M-1 Propellant Fires in Closed Conveyors, ARLCD-CR-78023, February, 1978.

EFFECT OF ENVIRONMENTAL INFLUENCES ON ULTRAVIOLET DETECTOR RESPONSE

By

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ABSTRACT

Studies were conducted to determine the influence of solid propellant manufacturing environments on ultraviolet (UV) energy absorption and transmission. Simulated environments studied included liquid, solid, and gaseous phases associated with process volatile solvents, propellant and ingredient dusts, and decomposition gases from a propellant fire itself. Quantitative data were obtained concerning the effect of these environments on UV transmission as functions of film thickness, concentration in the viewing atmosphere, and of viewing distance. Test results are applicable for assessing safety and optimizing fire suppression system designs in propellant manufacturing operations.

INTRODUCTION

In modernized propellant manufacturing facilities, such as are under construction at Radford Army Ammunition Plant (RAAP), an important safety design consideration is early fire detection and quick suppression to prevent propagation between operating bays or equipment. Ultraviolet detection equipment is being considered to provide rapid detection and activation of a fire suppression system.

The sensing capability of the detector can be affected by processing solvents, vapors and condensed liquid film on viewing windows, dust in the surrounding atmosphere, or even decomposition gases from burning propellant. This study was undertaken to obtain quantitative information on UV transmission and detector response under different solid propellant manufacturing environments. This information has application for the current propellant manufacturing operations and for future use in other plants.

DISCUSSION

A. General

A Detronics Model R7302 controller and C7050B UV detector were utilized in this study. Although the R7302 controller has a self-contained circuit for automatic checking and digital display of certain malfunctions, testing of this feature was not within the scope of this study.

The Detronics UV fire detector uses a Geiger-Muller type detector which is sensitive to radiation in the wavelength range from 1850 to

2450 Angstrom units. This range falls outside the wavelength of UV from sunlight reaching the earth. Also, the detector is not activated by normal artificial lighting such as fluorescent, mercury vapor, or incandescent. Electric arc welders, lightning strikes, and x-rays or gamma radiation could cause detector activation or false trips, but such extraneous sources are not normally present during propellant manufacturing operations.

B. Test Setup

The test arrangement employed in this study is shown in Figure 1. The 2.4-meter test chamber contained the atmosphere or environmental condition under test. Quartz windows were used in tests where a sealed chamber was necessary (such as solvent vapors or decomposition gases) since ordinary glass or transparent plastic do not transmit UV energy in the wavelength of interest. The Model W866A portable flashlight type ultraviolet lamp was used throughout the experiments. The vapor circulation system shown was used in volatile vapor atmosphere tests.

Detector response was recorded on the oscilloscope as a voltage-time trace as shown in Figure 1. Detector responses were recorded both for reference condition (no environmental effect present except a normal air atmosphere) and test conditions. Detector response voltages under environmental test conditions were compared to the reference response voltage to determine percent response at the different environmental conditions.

Exploratory tests were performed to verify that burning multi-base propellant emits UV energy capable of detection by the Model C7050B detector and to determine what quantity of burning propellant would produce UV intensities comparable to the Model W866A portable UV source.

As seen from data in Table 1, as little as 57 grams of double-base propellant yielded UV energy which was comparable to the standard UV light generator. Taking the detector response to the Model W866A UV light source as 100 percent, response to propellant flames ranged from 90 to 94 percent for viewing distances of 2.4 and 1.2 meters. Propellant samples of 113 and 57 grams were burned outside the conveyor, at the end, to minimize smoke buildup. It is apparent that detector response is more dependent on distance than propellant quantity, since only that portion of the flame visible to the detector through the 90 mm square window opening would cause a response in the detector.

C. Results

1. Vapor Atmospheres

Detector response measurements through acetone and alcohol vapor atmospheres as seen in Figure 2 show that vapors of both solvents caused

FIGURE 1

BASIC TEST SETUP

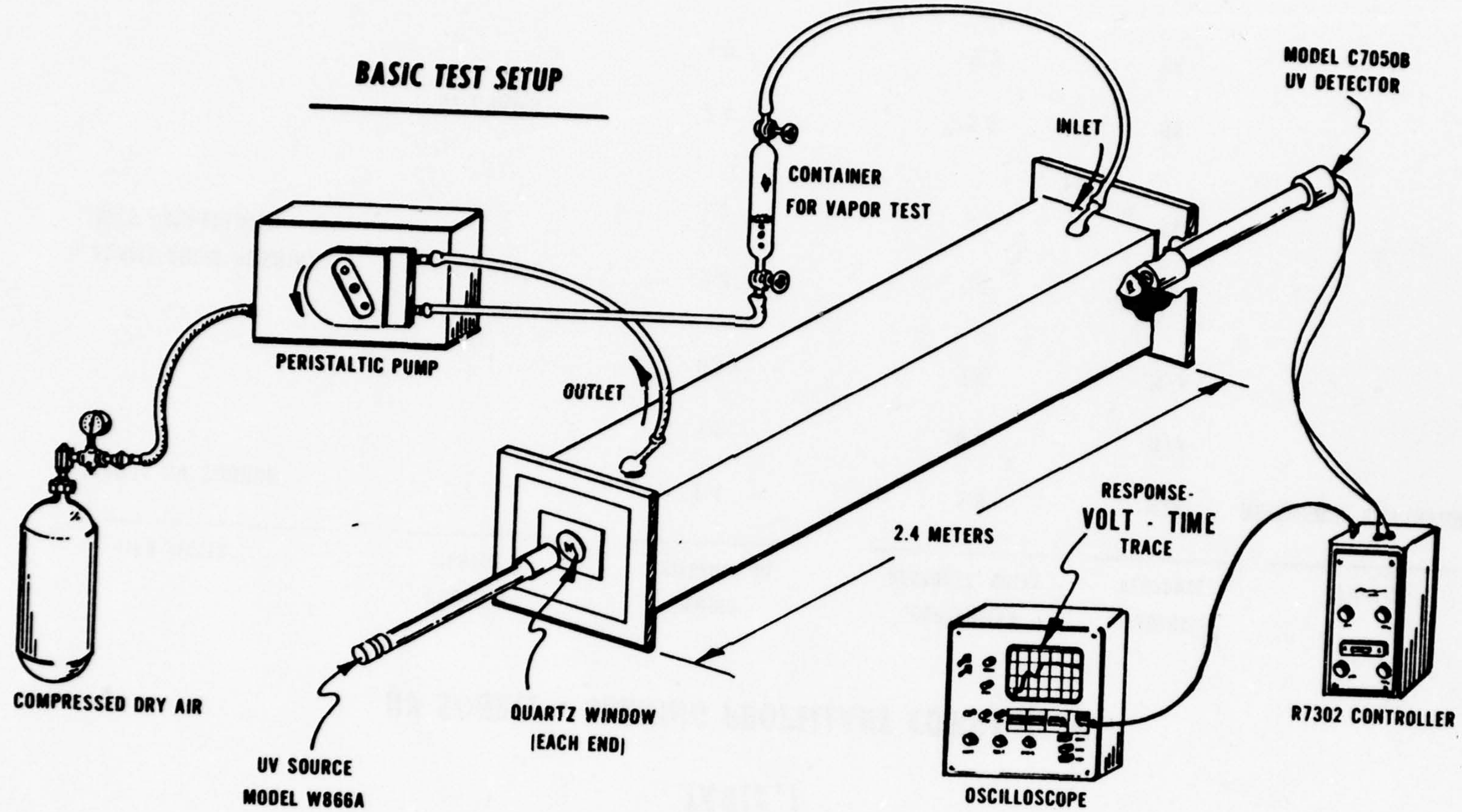


TABLE 1

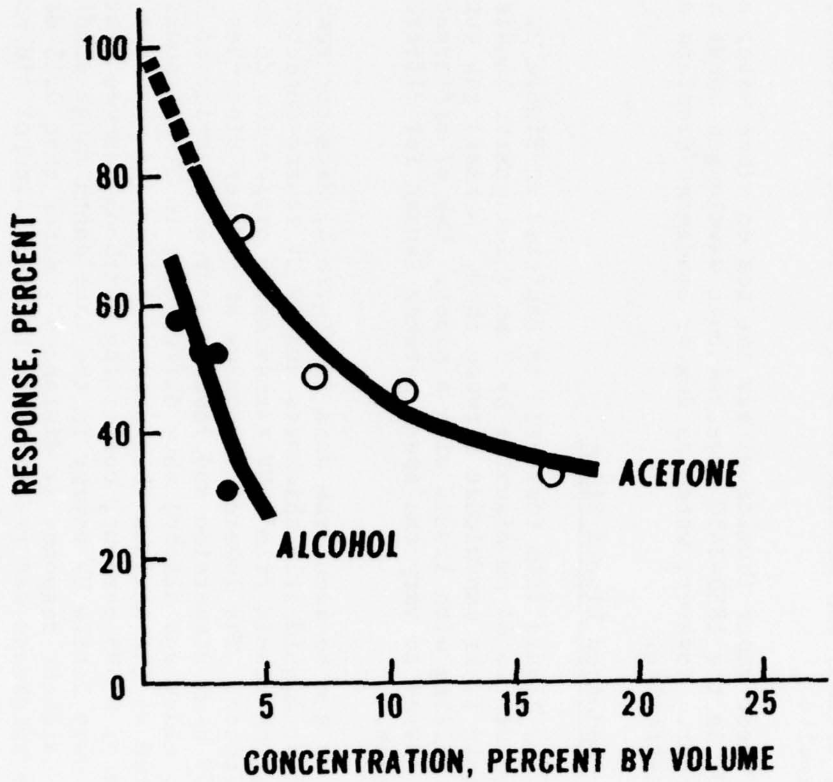
UV SOURCE - BURNING PROPELLANT COMPARISON

ITEM TESTED	QUANTITY TESTED	VIEWING DISTANCE, m	CONTROLLER RESPONSE, VOLTS	PERCENT RESPONSE [1]	REMARKS
W866A UV SOURCE	- - -	2.4	5.8	N/A	REFERENCE CONDITIONS
		1.2	6.6	N/A	
		0.15	7.6	N/A	
FLAME FROM BURNING M26 PROPELLANT	114 GRAMS	2.4	5.2	90	
		1.2	6.2	94	
	57 GRAMS	2.4	5.6	94	
		1.2	6.2	94	

[1] PERCENT RESPONSE, % = $\frac{\text{volts (flame)}}{\text{volts (referenced)}}$ AT A GIVEN VIEWING DISTANCE

FIGURE 2

UV RESPONSE THROUGH SOLVENT VAPOR ATMOSPHERES



attenuation of UV transmission. At maximum concentrations, response of the C7050B detector was 31 to 34 percent compared to the 5 to 6 percent required for controller actuation. Some degree of UV attenuation was expected since both solvents have absorption bands within the wavelength band of the C7050B detector. This attenuation is due to absorption of UV energy by the solvent molecules and is a function of vapor concentration.

The 3.3 percent alcohol and 16.5 percent acetone by volume concentrations tested are maximums attained in conveyor atmosphere tests at temperatures of 25-29°C. For comparison purposes, saturation concentrations of alcohol and acetone at 27°C are 10 and 32 percent, by volume, respectively.

Water vapor (humidity) was not tested since water alone does not absorb UV in the 1850-2450 Angstrom unit wavelength range seen by the UV detector. However, water as fog or condensed droplets could attenuate UV by scattering.

2. Condensed Liquid Films

The liquid film test cell is depicted in Figure 3. This cell consisted of two 64 mm diameter by 5 mm thick quartz lenses with the test liquid layer sandwiched between them. A small gap cut in the O-ring permits filling with liquid with a pipet. Use of different thickness O-rings served to vary the space between lenses for different film thicknesses.

As can be seen from data in Figure 4, detector response is affected by liquid film thickness and by UV source-detector distance. However, the liquid film's UV transmission properties do not change with distance. The lowered responses at greater distances are due to normal UV beam dispersion and lowered source intensity at longer paths. Acetone, ether and alcohol show differences in UV attenuation. Water was tested at the maximum thickness of 5.1 mm and showed a detector response of 93-95 percent, confirming textbook sources that pure water absorbs very little UV energy in the wavelength range studied. Acetone blocked detector response at distances greater than 0.15 meter when the film thickness was greater than 1.5 mm. Alcohol did not prevent detector response at thicknesses up to 5.1 mm.

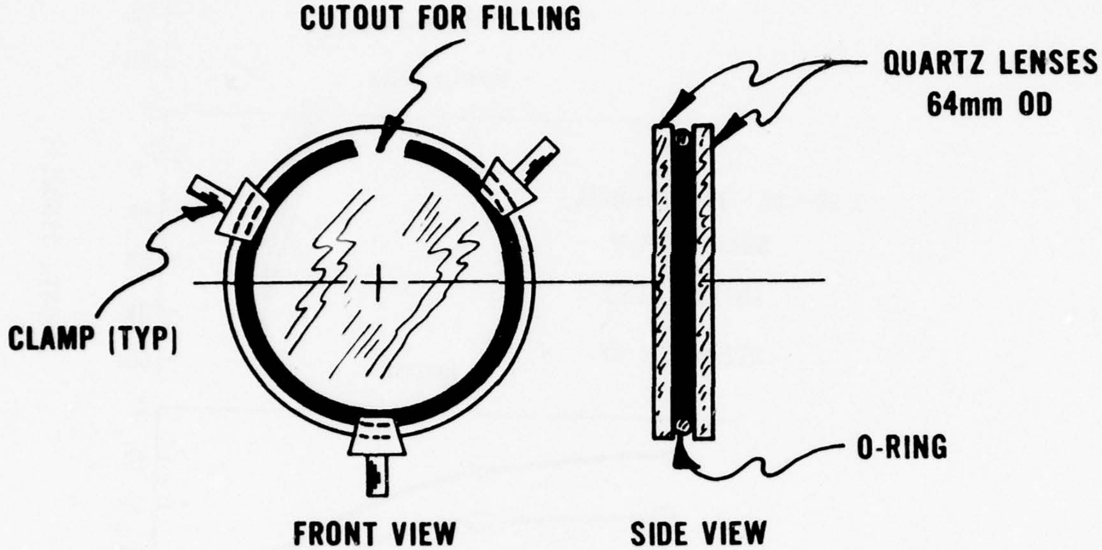
Natural film thicknesses expected in propellant manufacturing were determined to be approximately 0.1 mm (0.004 inch) indicating that little attenuation would be expected from liquid solvent films under manufacturing conditions.

3. Dust Layers

Dust layers are of concern because, unlike volatile solvents which evaporate, dust could accumulate in thicknesses sufficient to

FIGURE 3

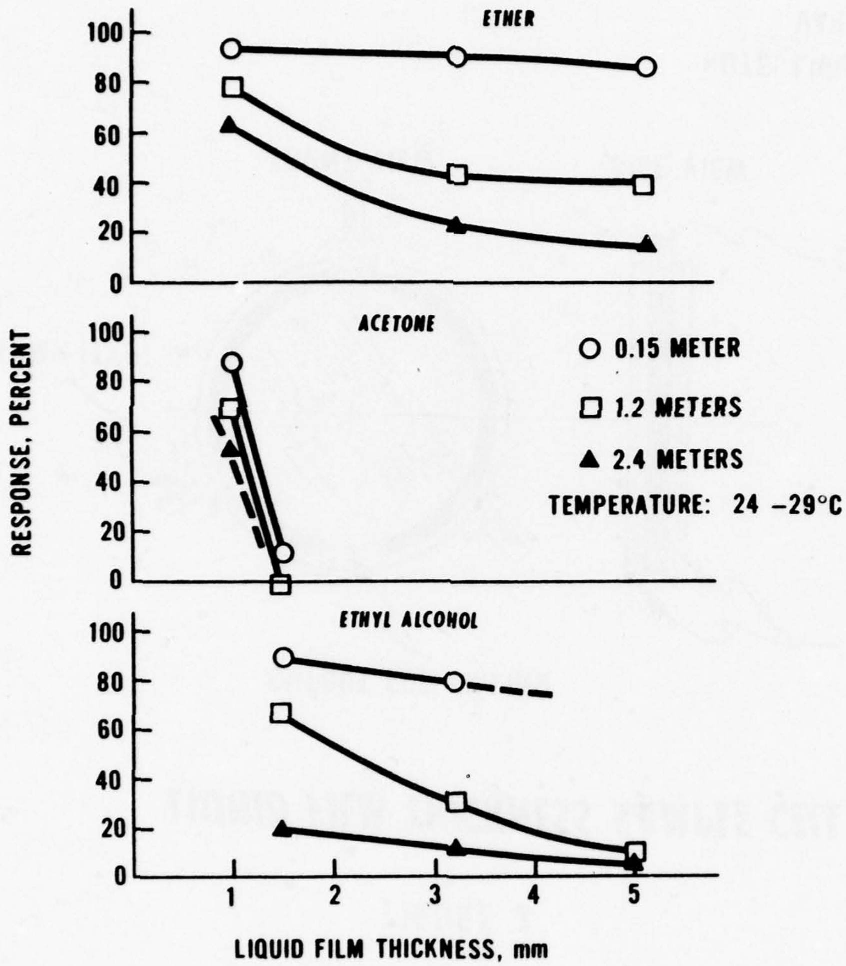
LIQUID FILM THICKNESS SAMPLE CELL



NOTE: LIQUID FILM THICKNESS
VARIED BY CHANGING
O-RING SIZE

FIGURE 4

LIQUID FILM THICKNESS AND VIEWING DISTANCE EFFECTS ON UV DETECTOR RESPONSE



block detector response. The test setup for dust layers is shown in Figure 5.

Results of ingredient dust layer tests are seen in Figure 6. The degree of attenuation for a given dust is a function of layer thickness and UV source distance. As noted with liquid films, the lowered detector response at greater distances is due to lower UV source intensity at longer path lengths and not to any change in UV absorption by the dust layer. Of the dusts tested, carbon black was found to cause the most attenuation, followed in order by nitroguanidine and cryolite. Ground propellant (M26 and M30) caused the least attenuation for a given thickness, as shown in Figure 6A. Reasons for differences between types of dust include particle size, density, and characteristic absorption of the material itself. The ground propellant had the coarsest particles and caused the least attenuation of the dusts tested.

On the basis of the above, detectors should not be placed where heavy dust accumulations are a problem, such as close to ingredient or dry propellant surge hoppers. Should dust be a problem in a given location, lenses should be cleaned frequently and/or an air purge attachment could be used to minimize dust coatings on the lenses.

4. Dust Atmospheres

Environmental dusts could attenuate UV transmission as seen by the UV detector both by absorption and scattering. Dust atmospheres were obtained by dispersing dry ingredient dust of carbon black, cryolite, and nitroguanidine into the conveyor interior atmosphere using compressed nitrogen. Dust concentrations were measured and tests were made at the 2.4 meter chamber distance only.

As is readily seen from data in Figure 7, UV attenuation was found to be affected by concentration and dust type. Carbon black caused the greatest attenuation, resulting in no UV detector response at a concentration of 1,000 mg/m^3. With cryolite dust, a response of 25 percent was obtained at a concentration of 1,050 mg/m^3. Cryolite concentration of up to 12,067 mg/m^3 blocked detector response, but settled rapidly (one minute or less) due to its relatively high density. Nitroguanidine dust could not be dispersed in sufficient concentration to block detector response. The nitroguanidine, even though of fine particle size (approximately 5 μ), tended to clump together and settle almost immediately so that very little remained dispersed.

The data show scatter due to the difficulty of dispersion and the rapid settling occurring. This scatter is partly due to concentration changes between response measurements and taking of air samples.

For application, results indicate that the maximum dust concentrations tested would not be expected under manufacturing conditions, even in closed equipment or conveyors since settling from the maximum

FIGURE 5

DUST LAYER TEST SETUP

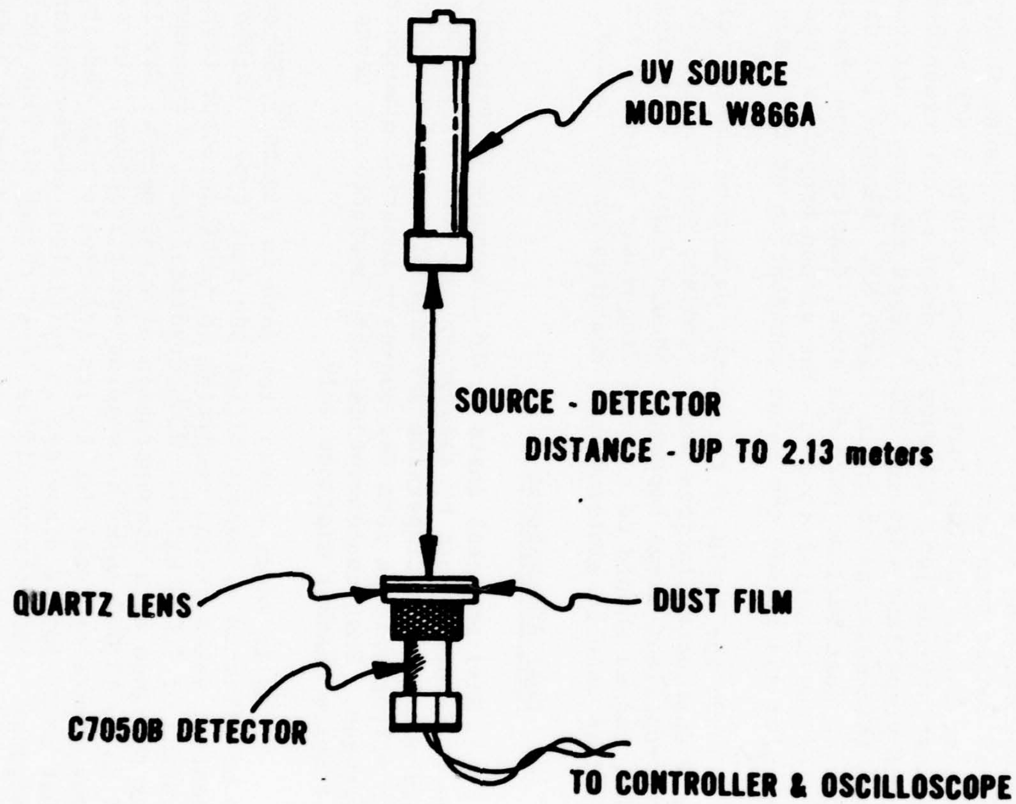


FIGURE 6

EFFECT OF INGREDIENT DUST LAYERS ON UV DETECTOR RESPONSE

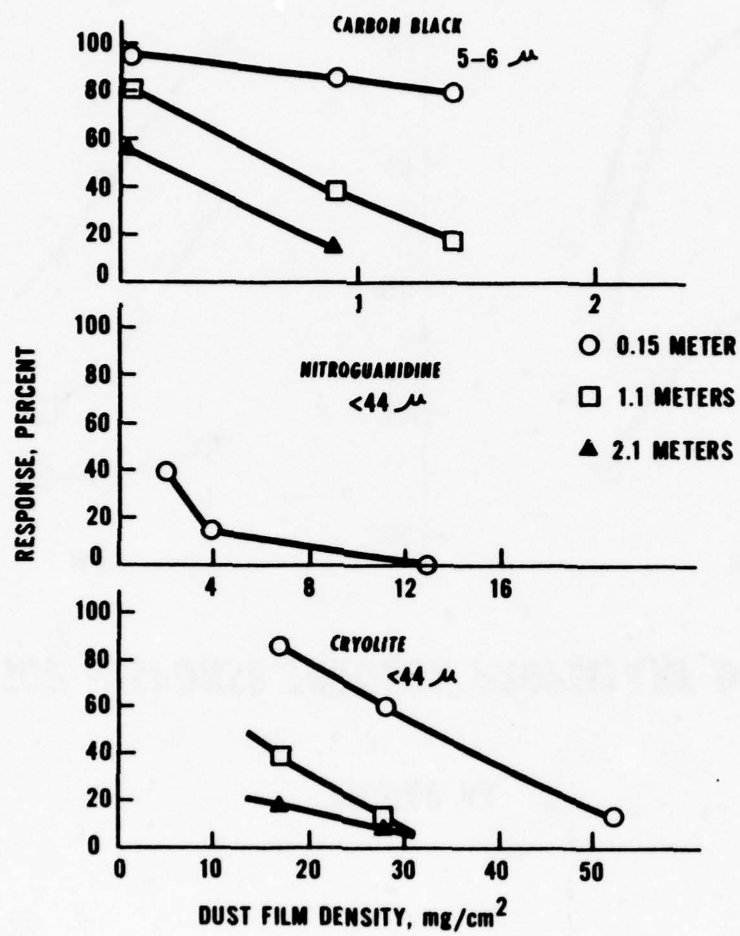


FIGURE 6A

UV DETECTOR RESPONSE THROUGH PROPELLANT DUST FILMS

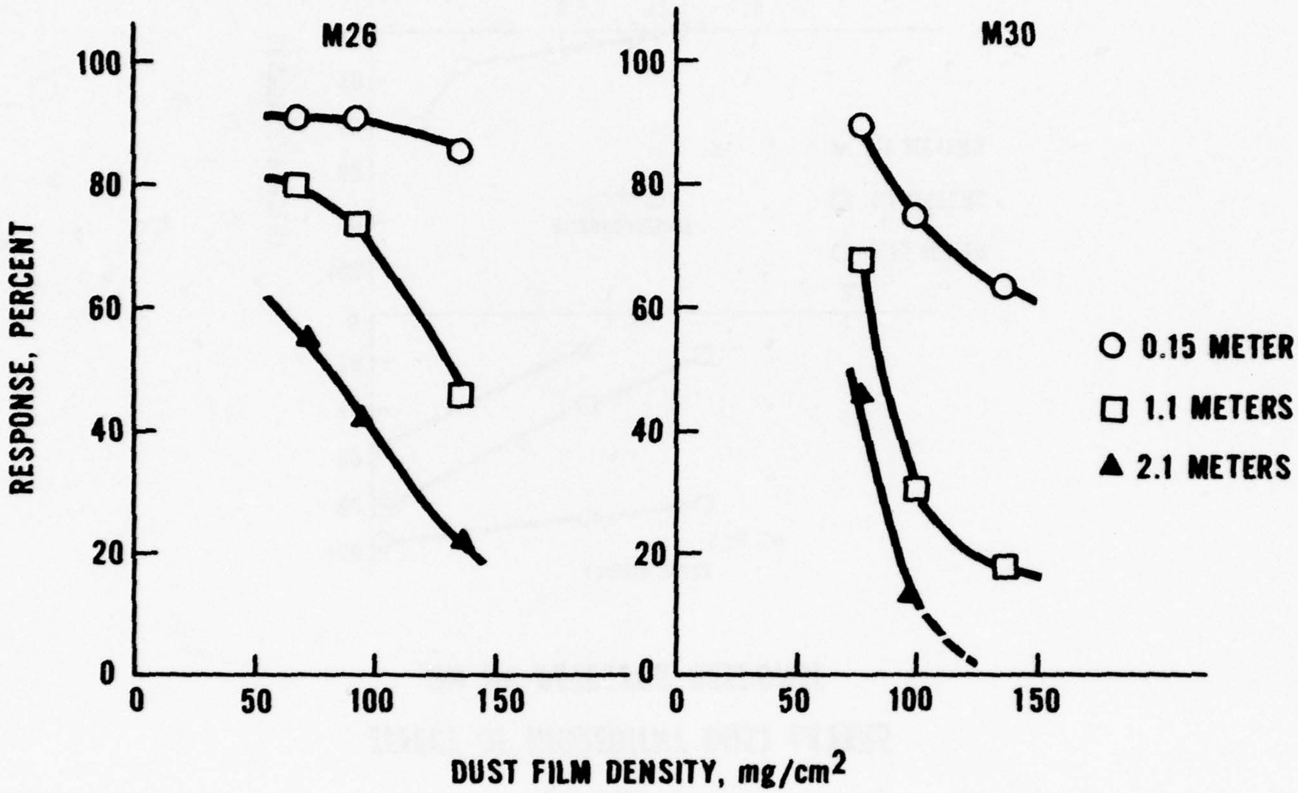
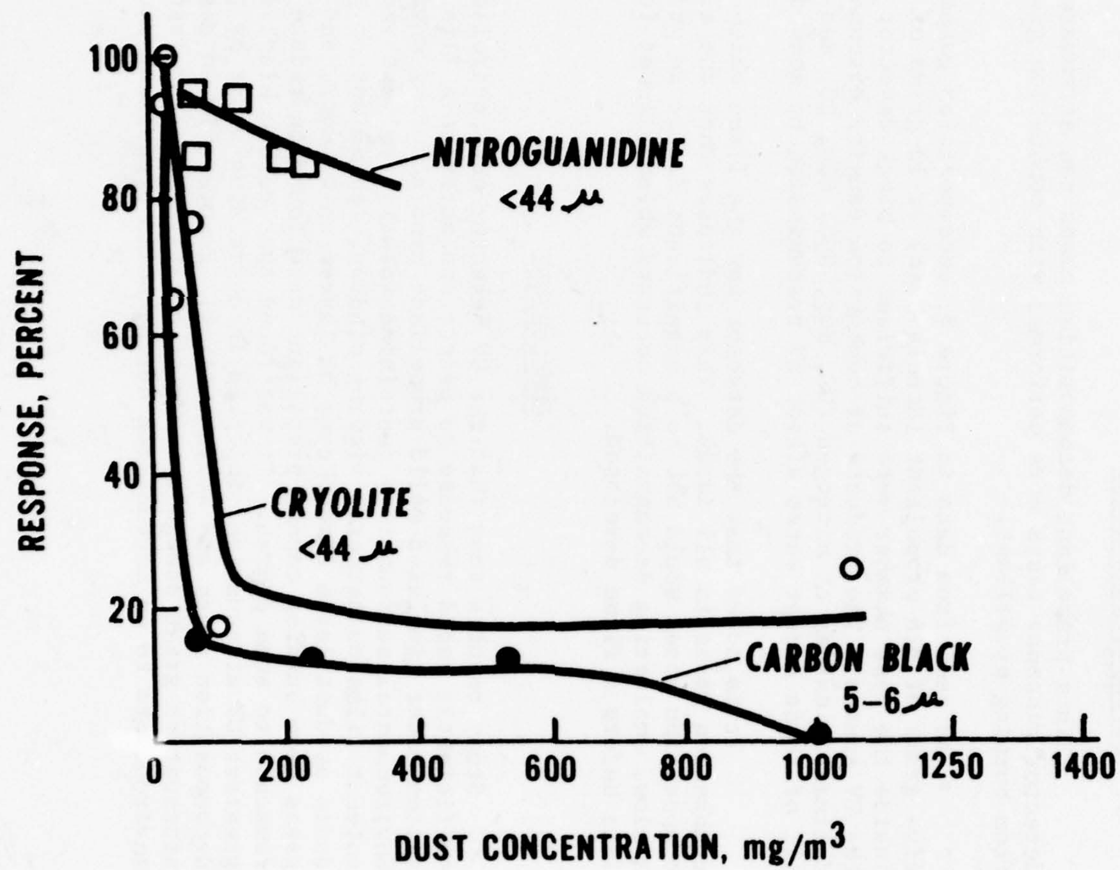


FIGURE 7

UV RESPONSE THROUGH INGREDIENT DUST/AIR MIXTURE



concentrations occurred rapidly. For open equipment and conveyors or bays, carbon black and cryolite concentrations would be less than those tested and little attenuation would occur. Nitroguanidine dust could not be dispersed in heavy concentrations and should not be a problem in manufacturing areas.

5. Decomposition Gases

Since propellant decomposition gases can attenuate UV transmission, detector response tests were performed with combustion gas atmospheres from burning propellant.

As seen from data in Figure 8, decomposition gases from burning five grams of M26 propellant (double-base) or 10 grams of M30 propellant inside the test chamber were sufficient to block detector response to the UV source. The products of combustion causing attenuation are predominantly oxides of nitrogen (NO, NO_2, N_2O) CO_2, CO, and water vapor. All of these except water affect UV transmission to some degree.

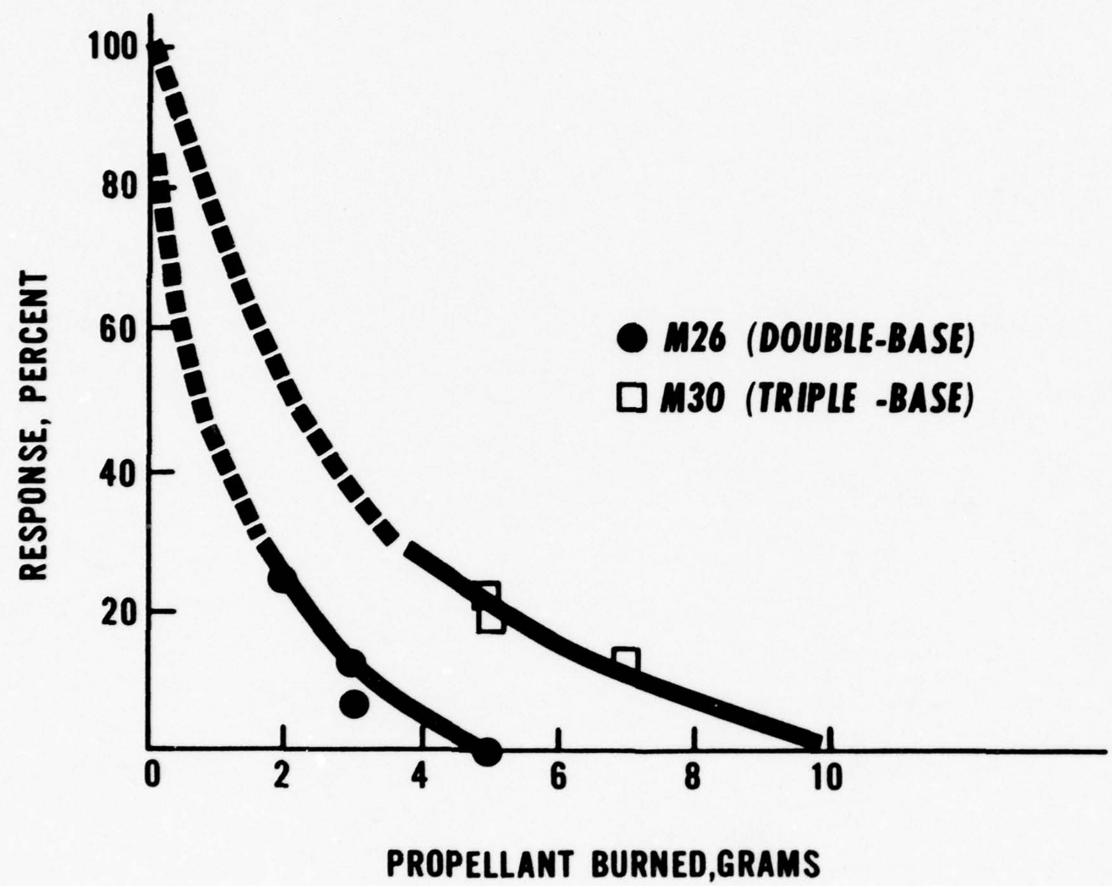
It is noted that the detector saw the flame which produced the combustion gases in all cases. This indicates that the effect of decomposition gases would not be a significant factor in practice unless a slow, smoldering decomposition occurred which allowed fumes to accumulate before a flame developed.

CONCLUSION

Study results show that the UV detector and controller provide sufficiently rapid response to detect and activate a fire suppression system under simulated solid propellant manufacturing environments. Environmental surroundings containing volatile solvent vapors or liquid solvent films on detector viewing windows, ingredient or propellant dusts as dust laden atmospheres or layers on windows, and decomposition gases from burning cannon propellant were found to reduce UV detector response to some degree. It was found that carbon black dust caused the greatest UV attenuation, followed in decreasing order by propellant decomposition gases and solvent films. However, in no case was UV attenuation great enough to prevent positive detector response for environments to be encountered during solid propellant manufacture.

FIGURE 8

UV RESPONSE THROUGH PROPELLANT COMBUSTION GASES



UNDERWATER EXPLOSIONS RESEARCH - A SHORT LOOK

by

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For some forty years, the Underwater Explosions Research Division (UERD) of the David W. Taylor Naval Ship Research and Development Center has carried out experiments in the field of underwater explosions (UNDEX) shock. Even before this the need to study the effects of underwater explosions was recognized as early as the 1860's, with the first experiments in the United States reported in 1881. For example, one such study conducted in 1908 used the monitor USS FLORIDA to determine the effects of torpedo impact on a ship's hull.

In the years prior to World War I, all of the major naval powers conducted experiments to improve ship hull protection measures. During the war, the use of torpedoes and floating and anchored mines pointed out the damaging effects which could be suffered by ships, as well as the need for better protection against these devices. In the interval between World War I and World War II, much effort was expended to develop and improve hull designs to reduce the effects of contact hits.

Due to the political conditions developing in Europe in 1938, with the threat of war growing steadily, interest in ship protection systems was especially strong. A small research group was organized in the Design Division of the Norfolk Naval Shipyard (NNSY) to study the performances of ships when subjected to underwater explosions. Experiments were carried out in the Turning Basin of NNSY utilizing scale models of battleship and carrier protection systems at various attack severities. One such result of this early work in the field of UNDEX research was the development of torpedo side-protection systems.

More sophisticated weapons, such as proximity-fused mines and more powerful torpedo warheads, were used during World War II and

resulted in intensified study of the effects of underwater explosions. In 1946, after suffering war time losses of 47 major ships and 52 submarines, the Bureau of Ships (now NAVSEA) established UERD. Initiated as a division of the Planning Department of NNSY, UERD was tasked to improve the resistance of ships and submarines to underwater explosion attacks, to determine ways to assess the effects of underwater explosions on ships, and to provide guidance to improve the effectiveness of weapons.

Since 1946, UERD has conducted almost 9,000 accident-free underwater explosion experiments. This work has included full-scale shock tests of operational ships down to small scale models. The operational ship tests involve explosive charges weighing up to 40,000 pounds. Through the use of scale models, UERD has become involved in such areas of research as torpedo side protection systems, fatigued structures, elastic-plastic response of cylinders, vulnerability of torpedoes, and many others.

The great majority of these UNDEX tests are conducted in the Turning Basin of NNSY, where charges up to 150 lbs may be used. When instances occur that require larger charges, or water depths greater than that of the Turning Basin, remote sites are used.

Examples are:

Key West Area	-	Full-Scale Hulls and operational ships in 1972.
Tongue of the Ocean Area Bahamas	-	Deep sea tests of Scale Submarine Models.
Cape Charles, Chesapeake Bay	-	Tested section of glass-reinforced plastic (GRP) Minesweeper hull in 1971.
Andersons Deep, Cheseapeake Bay	-	Submarine Shock Test Vehicle (SSTV) in 1970 and 1977. Submarine Models. Captive Air Space Craft (CASC). Free water tests.

Guantanamo Bay, Cuba	- Full Scale ship tests.
Open Ocean	- Full Scale ship tests.

Whether the underwater explosion experiments are conducted at NNSY or a remote site, the Underwater Explosions Barge (UEB-1) is the principal facility involved. Constructed in 1942, the original UEB-1 has been enlarged and modernized over the years until it has reached its present length of 185 feet and width of 50 feet. Aboard the barge are sleeping quarters for 64, a machine shop, electrical shop, conference room facilities, photographic processing equipment and diesel-generator power. Although a self-sufficient facility for test purposes, it has no means of propulsion and must be towed by a tug to each remote test site.

The UEB-1 also contains instrumentation handling equipment and recording centers with a nominal capacity of 150 channels of dynamic measurements of strains, displacements, pressure, acceleration, and velocity of the items being tested.

The primary personnel type services offered by the UEB-1 while engaged in underwater explosion testing are three fold:

1. To handle and position explosive charges and targets for each test.

2. To fire the charges and record the dynamic measurements.

3. To make repairs and design modifications to equipment that is required in a test series.

To evaluate the shock performance of actual shipboard equipment and systems, one of the various test vehicles maintained by UERD may be employed.

The first of these is the Full-Scale Section, or FSS-5. A large diameter cylinder, the FSS-5 is used in the testing of submarine hull fittings and valves. The FSS-5 is able to be submerged to the proper test depth by remotely controlled air lines attached to the vehicle's ballast tanks. Explosive charges are then detonated at various distances from the pressure hull to produce the appropriate shock loadings.

Secondly, we have the Floating Shock Platforms, or FSP's. As the name implies these are rectangular floating platforms measuring

28 feet long and 16 feet wide with a double bottom 3 feet thick. Initially developed by UERD, the Floating Shock Platform is used to shock test heavy weight surface ship equipment.

Another test vehicle is the Submarine Shock Test Vehicle, or SSTV. The SSTV is a stiffened cylinder representing a section of a submarine. Because of its size, not only large submarine hull fittings and valves, but complete internal and external systems can be shock tested in its large test compartment.

To conduct a test using the SSTV, the vehicle is submerged by flooding its end ballast tanks and then maintaining the specified test depth by means of two floats. Explosive charges ranging in size from 125 to 10,000 lbs have been used when testing equipment installed in the SSTV in its two test series conducted to date.

In addition to these test vehices, special test vehicles and structures are developed by UERD as they become necessary.

In summary, since 1946 UERD has participated in innumerable tests which have contributed significantly to the aim of insuring the Navy of surface ships and submarines with increasing resistance to underwater explosions and to the development of improved weapons. Full scale shock tests of surface ships are still conducted, with such a test scheduled this month.

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BLAST PREDICTIONS FOR TRIDENT TEST LAUNCHES*

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ABSTRACT

Early tests showed that C-4 motors provided for Trident I missiles could explode with as much as 50 ton TNT equivalent yield. Several design changes were made to eliminate this possibility, but strong assurance against an explosion could not be established before the flight test program was begun in early 1977. A Trident launch test facility had been prepared only two miles from the city limits of Cape Canaveral, Florida, before this hazard was identified. Significant damage to this community was threatened in event of an accidental detonation near the launch pad during flight testing.

Damage hazards could be greatly reduced by operating only when strong airblast attenuation was predicted. Trident test flights were therefore restricted to be launched only during good gradient propagation conditions in the direction of the city. Damage expectations were thus limited to an acceptable level, below 100 window panes broken in the community. This paper details the airblast prediction and the meteorological observation and evaluation programs that were developed to cope with this situation.

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BLAST PREDICTIONS FOR TRIDENT TEST LAUNCHES

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INTRODUCTION

Early static tests, begun in 1974, demonstrated that C-4 motors provided for the Navy's Trident I missiles could explode with as much as 50 ton TNT equivalent yield. This results from use of new high-performance VRA-7 and VOP fuels. These XLDB (cross-linked double based) propellants are Class VII explosives. Previously, large missiles usually used Class II "explosive" fuels that destruct by conflagration rather than detonation.

A Trident launch test facility had been built at Pad 25, Cape Canaveral Air Force Station (CCAFS), before this explosion hazard potential was identified. This pad is only 3 km from the city limits of Cape Canaveral, 5 km from the town center, as shown by the map in Figure 1. About thirty test flights were planned from this location in 1977-1978 before the Trident was scheduled for sea trials. In event of an accidental explosion near the launch point during these launch tests there could be significant damage to the nearby community.

A hazard analysis of the planned tests was begun at Sandia Laboratories in late 1975, sponsored by the U.S. Navy Strategic Systems Project Office (SSPO). An assessment of the explosion yield potential was made at Los Alamos Scientific Laboratory. Airblast propagation predictions made for various weather conditions showed that up to 7kPa (1 psi)

overpressures could reach Cape Canaveral under some common atmospheric conditions. Under the best of conditions, with propagation strongly attenuated by upward refraction of the airblast wave, some window damage could still be expected. A detailed evaluation was needed to determine what level of airblast propagation could be accepted and how often suitable weather conditions would be encountered.

A survey of building structures and window panes was made in January 1976. Analyses showed that damage could be limited to a "few dozen" window panes by a restriction that only allowed test launches during weather conditions with a strong vertical gradient in sound velocity (giving strong upward airblast refraction) toward the Cape Canaveral community. Blast waves, under these weather conditions, would not be expected to cause any building structure damage. It was established from climatic data collections that suitable weather conditions occurred during all months of the year, but two to three days of weather delays could be expected statistically for most tests.

Design modification was made in the missile command destruct system to reduce the likelihood of an explosion under accidental or commanded flight termination. Two tests at White Sands showed that this design change was effective, but an absolute assurance of no explosion was not possible.

A launch test plan was adopted to fire only under weather conditions that met the multiple criteria of a strong vertical

sound velocity gradient and no surface wind component directed toward Cape Canaveral. A weather observing, computer, and video display system was developed by the CCAFS Air Weather Service Detachment to show conditions at five-minute intervals. A system of five airblast pressure measurement stations was installed by Sandia Laboratories to document any blast waves that might be generated by an accidental explosion during the launch.

Fourteen test flights have been conducted (as of 6/22/78) without any accident or explosion near Pad 25. Weather delays have turned out to be somewhat less frequent than was expected. After eight tests, Sandia participation in the count-down "Weather Watch" and blast gaging was terminated for economy. CCAFS weather and range safety people had developed adequate appreciation, understanding, and experience to make this evaluation without our assistance.

Sandia and the USAF Space and Missile Test and Evaluation Command (SAMTEC) are now involved in assessing future missile system test plans, for the Trident II with a somewhat larger D-5 motor, for the USAF MX, and for the STS (Space Transportation System - "Shuttle").

BACKGROUND

The explosion yield for Trident I C-4 motors was determined by Craig [1] to be equivalent to 36 Mg (80,000 lb) TNT as a "best estimate," with an upper limit of 45 Mg (100 klb) TNT. A surface burst of this yield would give nearly the same air-blast as a free-air burst of 0.2 kt NE (nuclear explosion). Nuclear equivalence is used for yield-scaling of airblast characteristics from the AFWL Standard [2]. If exploded shortly after launch and near 141 m (464 ft) height-of-burst (HOB), as much as 0.6 kt NE apparent yield could result. Overpressure versus distance curves, yield-scaled for a surface burst condition [3], are shown in Figure 2 for the 45 Mg TNT upper limit.

Effects of atmospheric structure appear to be quite important in determining what overpressures can be expected at the range of Cape Canaveral. Even under the best of conditions (gradient), overpressures would be above the window damage threshold of 0.2 kPa (0.03psi). Near this distance there is considerable uncertainty about exactly how atmospheric refraction effects begin to dominate the propagation phenomena. It is not clear whether a blast gage would see a side-on pressure from horizontal wave travel as is generally observed "close-in", or a reflected (doubled) pressure from downward wave motion as is usually seen at long ranges. Also it is not clear how wave energy would be scattered or diffracted into a "silent" region or out of a sound duct.

At overpressures below about 5 kPa, glass failure depends primarily on overpressure loading. Compression rise time for these weak waves is usually larger than about 3 ms so that complex high-frequency inputs and responses may be neglected. Glass damage probabilities from airblast overpressures, shown in Figure 3 [4], have been estimated from the Medina explosion [5] near San Antonio in 1963 and various large explosion tests [6]. Calculated damage probabilities are much greater in community exposures than in laboratory tests because variances from pane orientation and atmospheric propagation are included in the calculation. Gaged overpressures that range from 10 kPa down to 0.2 kPa, under various weather conditions and in various parts of Cape Canaveral, would break from nearly all, down to 10^{-5} of the exposed window panes. To get a better estimate of this hazard, a detailed assessment was made.

HAZARD ANALYSIS

A survey of Cape Canaveral buildings and houses and their window panes was made in January 1976. Following the pattern of the San Antonio survey, four window pane size categories, described in Table I, were used in the Cape Canaveral census. The distribution of small panes was significantly different than in San Antonio. Florida architectural styling employed many canopy-type windows with relatively long, narrow panes for ventilation, rather than more nearly square panes in divided casements, so typical of the Southwest. Mean breaking overpressures and standard deviations for all panes, including the canopy panes, are also shown in Table I.

Cape Canaveral survey results, shown in Figure 4, were block-by-block counts of four pane size categories. Older housing (15-25 years) often had several jalousie windows, made up of narrow (15 cm) glass strips, that are quite resistant to low overpressure airblasts. This resistance was established at Johnston Island in 1958 and 1962, during high altitude nuclear explosion tests. These jalousies were ignored in our Cape Canaveral survey. Some residential blocks were not surveyed, once the general distribution of pane usage in relation to the number of detached and apartment buildings was established. Pane count estimates for these blocks were made from housing counts, obtained from aerial photographs of the town. Summary census statistics are shown in Table II. The total pane estimate of 44,905 panes, represents about 10.5 panes per capita, for comparison with 19 panes per person estimated for San Antonio in 1963 [5]. This difference is attributable to the difference in architectural styles. There are, however, many more large C and D panes per capita in Cape Canaveral than in San Antonio. This reflects a newer community, an ocean view from many locations, and a higher proportional density of retail commercial establishments in a tourist-related economy.

A damage assessment was calculated using gaged (reflected) overpressure isobar radii, taken from Figure 2, and overlaid on the census map, for both gradient propagations and inversion ducted propagations (3X overpressure magnification above standard). Damage probabilities for these overpressures, from

Figure 3, were multiplied by pane counts and summarized in Table III. Results show that under weak propagation conditions the hazard would be small and the few broken panes could be repaired at minor cost in both dollars and public relations. On the other hand, propagation enhanced by a night-time or early morning temperature inversion, or in downwind directions, would break nearly 40% of the town's panes. There would be considerable hazard from this large quantity of breaking and broken glass.

The safety hazard from flying window fragments, carried by a Trident explosion wave, was assessed by Fletcher, Richmond, and White [7]. They generally concluded that acceptably low overpressures would not cause hazardous glass missiles, but falling glass from very large panes or multi-story buildings could be a significant hazard.

Further evaluations made jointly by Lockheed Corporation engineers and Patrick AFB range safety officials, using various other flight failure models, arrived at similar conclusions. It was concluded that Trident I test flights should only be conducted under weather conditions that strongly attenuated propagation in the critical direction toward Cape Canaveral.

Evaluations for other directions toward other communities were also made. Although they have larger populations, they are at greater distances, and less severe weather restrictions were found necessary.

CLIMATE ANALYSES

Weather observing facilities at Cape Canaveral included a rawinsonde balloon station and a number of meteorological towers equipped with wind and temperature sensors. A review of historical rawinsonde records showed that during each of three months of the year there would be less than ten "good" days, while in another three month period there would be less than ten "bad" days. On the average, it appeared that two to three days of delay could be expected for each launch, while awaiting appropriate weather conditions.

Since rawinsonde balloon ascensions are usually made only twice daily, morning and evening (at 0000Z and 1200Z), they are not representative of midday conditions. Maximum afternoon surface temperatures could be expected to improve conditions (attenuate propagations), so that there would be appreciably more good days than were indicated by the rawinsonde data.

On the other hand, this coastal site is strongly influenced by a sea breeze that blows from ocean to land in the daytime, and from land to ocean at night. A detailed study of tower meteorological observations [8] showed that high surface temperatures (good) are usually accompanied by wind components toward Cape Canaveral (bad), unless the general circulation above the boundary layer is strong from the west or south.

It was concluded that weather restrictions on test schedules would be expensive, but not nearly so expensive as (a) extensive property damage and injuries in event of an accidental explosion,

or (b) moving the test program to a more isolated launch pad with about a year of delay for the entire Trident program.

ATTEMPTED PREDICTION REFINEMENTS

In Figure 2 inversion propagation is shown giving 3X magnification of overpressures. This is an extreme value taken from statistical experience with both nuclear and large chemical explosions. Average inversion and downwind propagations were only enhanced by factors of 1.5 to 2. It is intuitively obvious that inversion strength and depth should influence this degree of magnification. But extensive and detailed boundary layer data, necessary to determine the correlation, were not obtained during most explosion tests. One Sandia attempt, in 1959 at Nevada Test Site, with 1.1 Mg (2500 lb) TNT explosions, gave ambiguous results that could not be adequately resolved [9].

The Army Engineers' Construction Engineering Research Laboratory (CERL) conducted an extensive experiment at Fort Leonard Wood, MO, in 1973 [10]. They operated seven sound level meters at 300 m to 24 km distances on each of four gage lines in a cruciform array centered on 2.3 kg (5 lb) explosive sources. Over 700 shots were fired at about five minute intervals on twelve days of June. Unfortunately, their weather data collection was deficient, so that no good correlation could be made between propagations and boundary layer conditions. Figure 5 shows the large scatter of amplitudes obtained at 3.2 km (2 miles) range versus the directed

sound velocity change in the lowest 300 m of the atmosphere. Further analyses are being made for other gage distances in this CERL collection in hopes of refining the correlation. It may be, however, that such short duration (24 ms) waves from only 2.3 kg sources cannot be accurately scaled to larger yields, because of atmospheric turbulent attenuation of high frequency components. From overall appearances in Figure 5, the conclusion was that weather restrictions adopted for Trident flights may not have been sufficiently stringent. Nevertheless, a policy change based on such ragged data could hardly be justified.

The Naval Surface Weapons Center (NSWC) was conducting some Trident-related, 454 kg (1000 lb) HE tests at Dahlgren NAS, VA, in 1977 [11]. Three airblast gage lines and detailed weather observations were added to their program for three events, with results shown in Figure 6. Most of these few data points showed an encouraging correlation, but the one set showing the strongest propagation was obtained upwind from a shot. This shot was fired at 3 m above the water surface of the Potomac River, while the other two were fired at 1.5 m above the water. One tentative explanation of this anomalous result is that HOB effects may be enhanced toward upwind directions, for some HOB's. This needs considerable further exploration, not only for immediate Trident concerns, but for general weapons effects purposes.

OPERATIONS

A weather criteria chart shown in Figure 7 was agreed upon for delineating "good" and "bad" conditions. A "good" gradient toward Cape Canaveral was required to have at least $-0.005\ s^{-1}$ (-5 ft/sec per thousand feet) decreasing sound velocity with height to 1.2 km (4000 ft) altitude. Toward Merritt Island, at greater range, no enhancement above standard propagation was allowed. A small margin of safety was imposed to allow for measurement error and wind variability. Toward towns at even larger distances, standard propagation or even a moderate strength, shallow inversion could be tolerated. A shallow inversion could be expected to cause sufficient wave scattering from multiple ground reflections to prevent damaging overpressures at long range. Ducting by upper air conditions, with possible focusing at the 90 km distances of Vero Beach (south) and Daytona Beach (north), but with very low probability of striking a specific place, would be assessed on a case-by-case basis.

This criteria chart is used as a backdrop for a video display of current observations in the CCAFS Weather Station. Rawinsonde balloon observations can be made at as short as one hour intervals during a launch count-down, and results are fed into the computer. Also, meteorological tower data, at five minute intervals if required, are fed automatically to the computer. The computer calculates sound speeds versus height from temperature reports, resolves wind components for selected azimuths, and adds them to sound speeds to give directed

sound velocities versus altitude. The operator selects an azimuth and the computer gives a video screen display of the latest directed sound velocity difference curve for comparison with the safety criteria for that direction. Conditions must fall to the left of the criteria curve at all altitudes for acceptability . Other computer outputs are also available on command, including numerical output tabulations, time trends, and hard copy.

In a typical Trident test count-down there are several critical times for weather-dependent decision-making. Missile tracking ships need to be sent to their stations with two or three days notice, worker shift schedules need to be set a day ahead (longer on weekends), down-range aircraft need to take off several hours before a missile launch, local range safety surveillance ships and helicopters need to be dispatched, some other launch complexes need to be cleared, and roads need to be blocked with 30 to 60 minutes notice. Certain critical missile functions need to be activated within the final fifteen minutes. In result, the weather watch becomes intense at about H-6 hours.

Accurate predictions for two or three days would be valuable, but an analysis of wind forecasting potentials showed that the errors would probably be too large to allow a net cost savings. The cost of missing a good firing day because of an erroneous forecast would be more than the cost of wasting the time of ships, aircraft, and work crews. In consequence, only on rare occasions was a launch delayed

before the early morning count-down actually started. Conversely, some counts were continued in spite of almost futile odds against sufficiently improved weather.

Five airblast pressure gage stations were installed and operated by Sandia to document airblast waves in the event of an accidental explosion during a Trident launch. The gage system has been described elsewhere [12]. Gage signals were radio telemetered to a central recording station in Hangar F of the CCAFS industrial area. Gages were placed [see Figure 1] 1) north of the entrance to Port Canaveral, 2) near the south gate to CCAFS, 3) near the beach in Cocoa Beach and about 1 km south of Cape Canaveral's city limits, and 4) at the east end of a causeway between Kennedy Space Center and Titusville. The fifth station was placed at Launch Complex 17, about 2 km from Pad 25, to document impacts on large Delta missiles which were also in preparation for testing. This pressure gaging system was operated during eight tests, but it collected no data because there were no explosions to record. Its operation was then discontinued as an unnecessary expense as Trident reliability became better established.

RESULTS

Since there were no explosive failures near launch from fourteen Tridents, there was no damaging or hazardous blast wave imposed on the communities around CCAFS. The test

schedule in Table IV shows that predictions for the number of weather delays were well verified. Since there were no explosions near the launch area, there could be no verification of the airblast, damage, and hazards predictions.

Meteorological data acquisition and processing, as it finally evolved, was a great success. It demonstrated how much information could be made available on a well-instrumented test range with modern computer technology. Video display outputs aided briefings and helped decision-makers to better understand the weather factors that were important.

CONTINUING STUDIES

The principles and procedures developed for this test program are being applied to evaluations of tests planned for future large missile systems. The next generation Trident II D-5 is being considered, along with the USAF M-X and the STS-Space Shuttle, to help select a test site where weather restrictions on acoustic propagation will not be prohibitive.

SUMMARY

Trident missile motors may explode during early launch phases, with a sufficiently large yield that could cause considerable damage to neighboring communities. This airblast must be strongly attenuated by the atmosphere in order to hold damages down to an acceptable level in the event of an explosion. Meteorological criteria for

proceeding with a test were established which assured satisfactory attenuation. A weather watch was instituted for Trident tests, which included rawinsonde balloon and meteorological tower observations, along with a computer calculation of acoustic refraction conditions. The system has worked reasonably well at Cape Canaveral. Weather delays have averaged approximately two days per test.

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Table I. Window Pane Category Definitions

Pane Category	Pane Area (m^2)	Pane Area (ft^2)	Median Area (m^2)	Median Area (ft^2)	Assumed Thickness (mm)	Assumed Thickness (in)	Gage Overpressure 50% Damage (kPa)	Gage Overpressure 50% Damage (psi)	Geometric Std. Dev. Factor	Glass Description
A	≤0.2	≤2	0.09	1	2.03	0.08	12.57	1.82	1.83	Single strength (SS) common
A_2*	0.2	2	0.18	2	2.03	0.08	6.29	0.91	1.83	SS common
B	0.2-0.8	2-9	0.56	6	2.03	0.08	2.10	0.30	1.83	SS common
B_2*	0.2-0.8	2-9	0.23	2.5	2.03	0.08	5.03	0.73	1.83	SS common
C	0.9-3.7	9-40	2.32	25	6.35	0.25	3.18	0.46	1.87	1/4" nominal,
D	≥3.7	≥40	4.65	50	9.53	0.375	3.58	0.52	1.87	3/8" nominal, polished plate

* Subscript 2 indicates Cape Canaveral awning window panes.

Table II. Window Pane Census for Cape Canaveral

Pane Category	Number Counted	Number Estimated	Total Number	Estimate from San Antonio per capita distribution*
A_2	16,603	5,969	22,572	45,177
B_2	11,787	7,953	19,740	34,916
C	2,234	52	2,286	596
D	307	0	307	169
Totals	30,931	13,974	44,905	80,858

*Population Estimates: San Antonio, 1963--660,000;
Cape Canaveral, 1977--4,258.

Table III. Estimated Window Damages in Cape Canaveral from 100 ton HE at Pad 25

	Panes Broken (% of exposed)	
Pane Category	Gradient Propagation	Inversion Propagation
A_2	0	4,321 (19%)
B_2	33 (0.17%)	11,311 (57%)
C	3 (0.13%)	1,379 (60%)
D	1 (0.33%)	216 (70%)
TOTALS	37 (0.08%)	17,227 (38%)

Table IV. Trident Test Schedule and Delays

	Scheduled Test	Actual Test	Delay Cause
1	1000 EST 1/17/77	1403 EST 1/18/77	28 hr delay, weather
2	1000 EST 2/14/77	1810 EST 2/15/77	32 hr delay; weather
3	1000 EST 3/25/77	1017 EST 3/28/77	3 day delay; hardware
4	0900 EDT 4/29/77	1009 EDT 4/29/77	1 hr delay; fishing boats
5	0700 EDT 6/27/77	0700 EDT 6/27/77	No delay
6	1000 EDT 8/10/77	1518 EDT 8/18/77	8 day delay; 4 weather, 3 weather forecast, 1 hardware
7	0700 EDT 8/30/77	1016 EDT 9/3/77	5 day delay; weather
8	0800 EDT 10/17/77	1408 EDT 10/19/77	2 day delay; weather
9	12/?/77	12/?/77	No delay
10	1/16/78	1/17/78	1 day delay; weather
11	2/14/78	2/14/78	No delay
12	4/12/78	4/12/78	No delay
13	6/18/78	6/22/78	4 day delay; weather
14	8/11/78	8/11/78	No delay

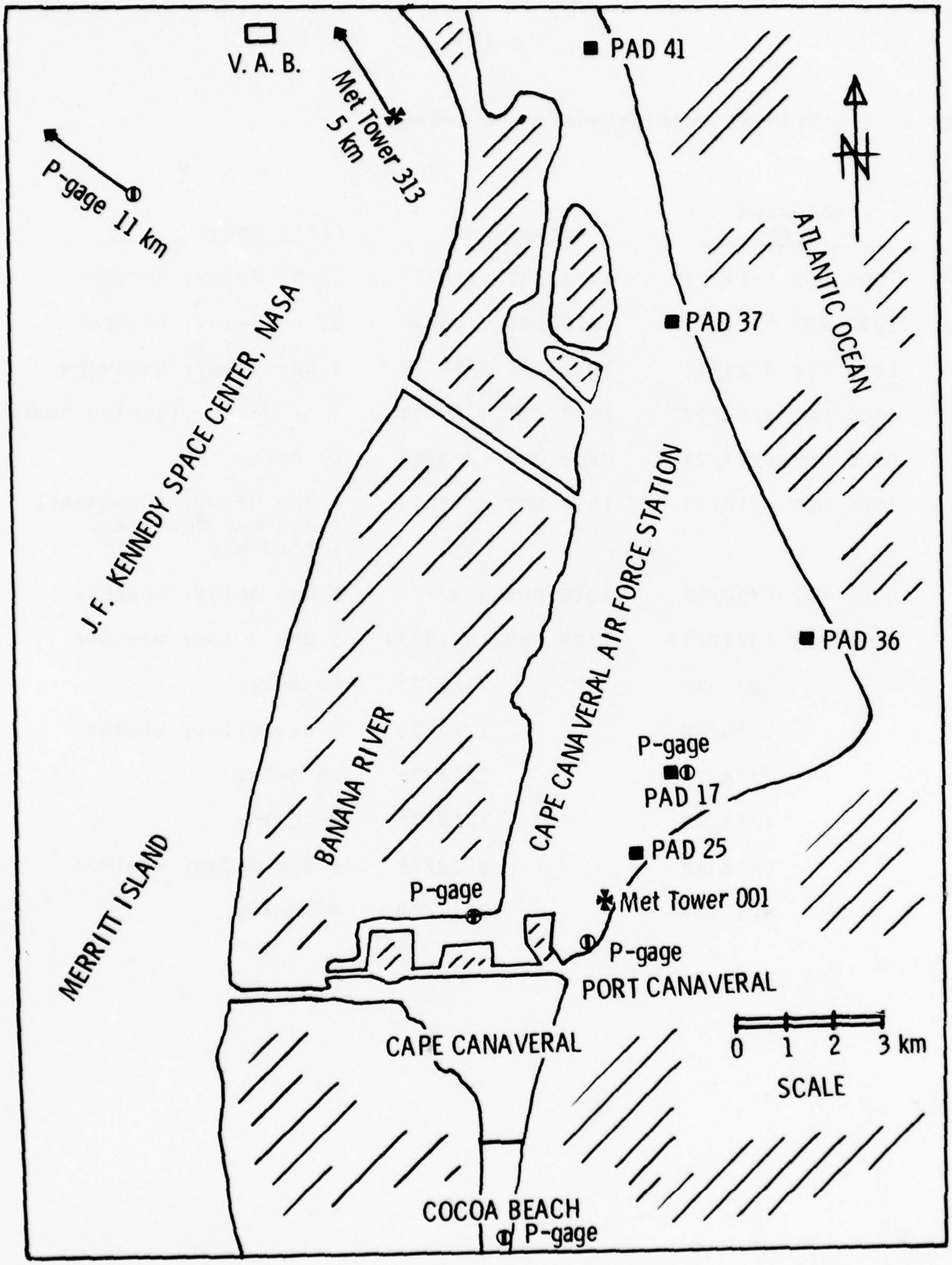


Figure 1. Map of Cape Canaveral, Florida

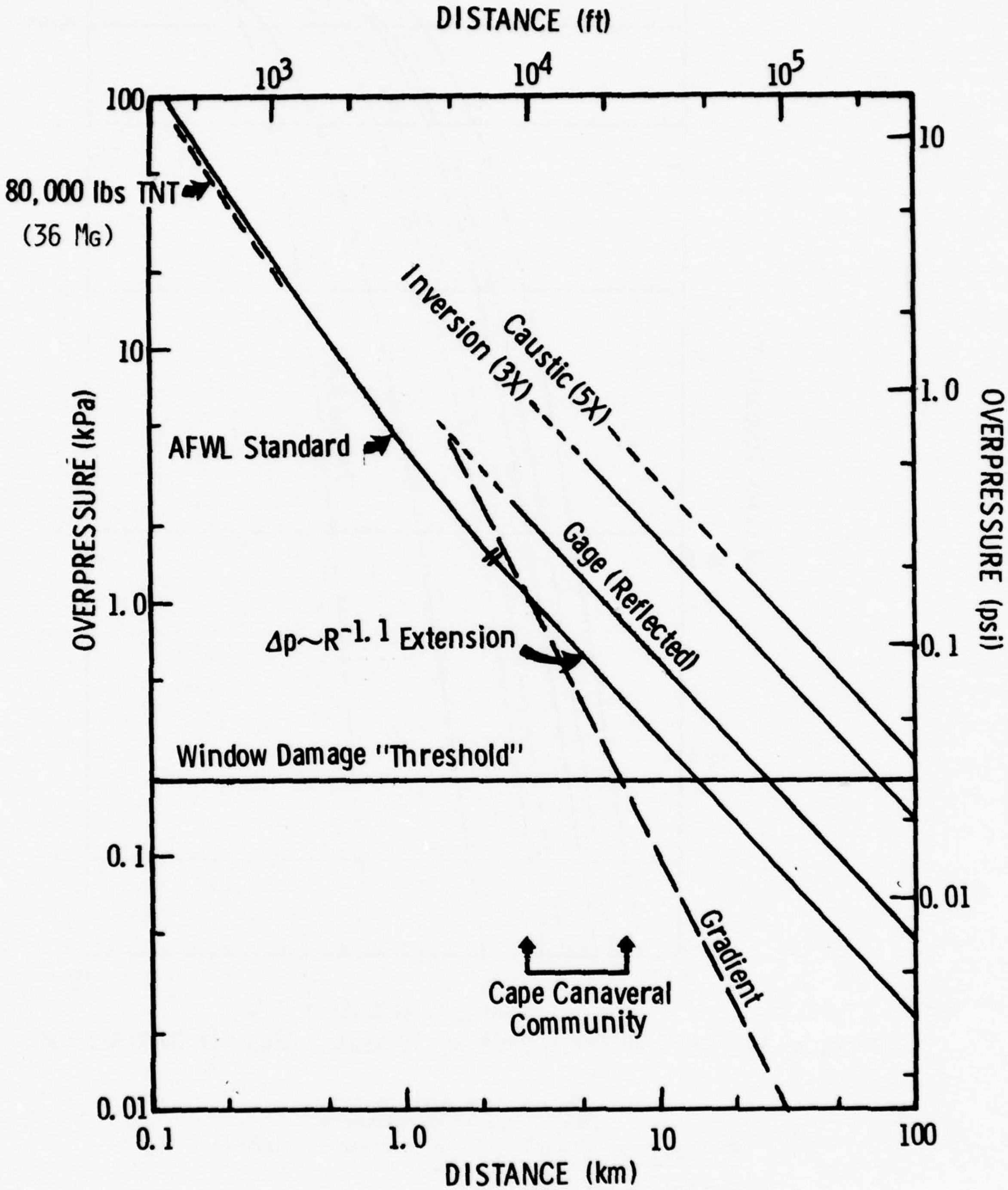


FIGURE 2. AIRBLAST PREDICTIONS
100,000 lbs (45 Mg) TNT Equivalent Surface Burst

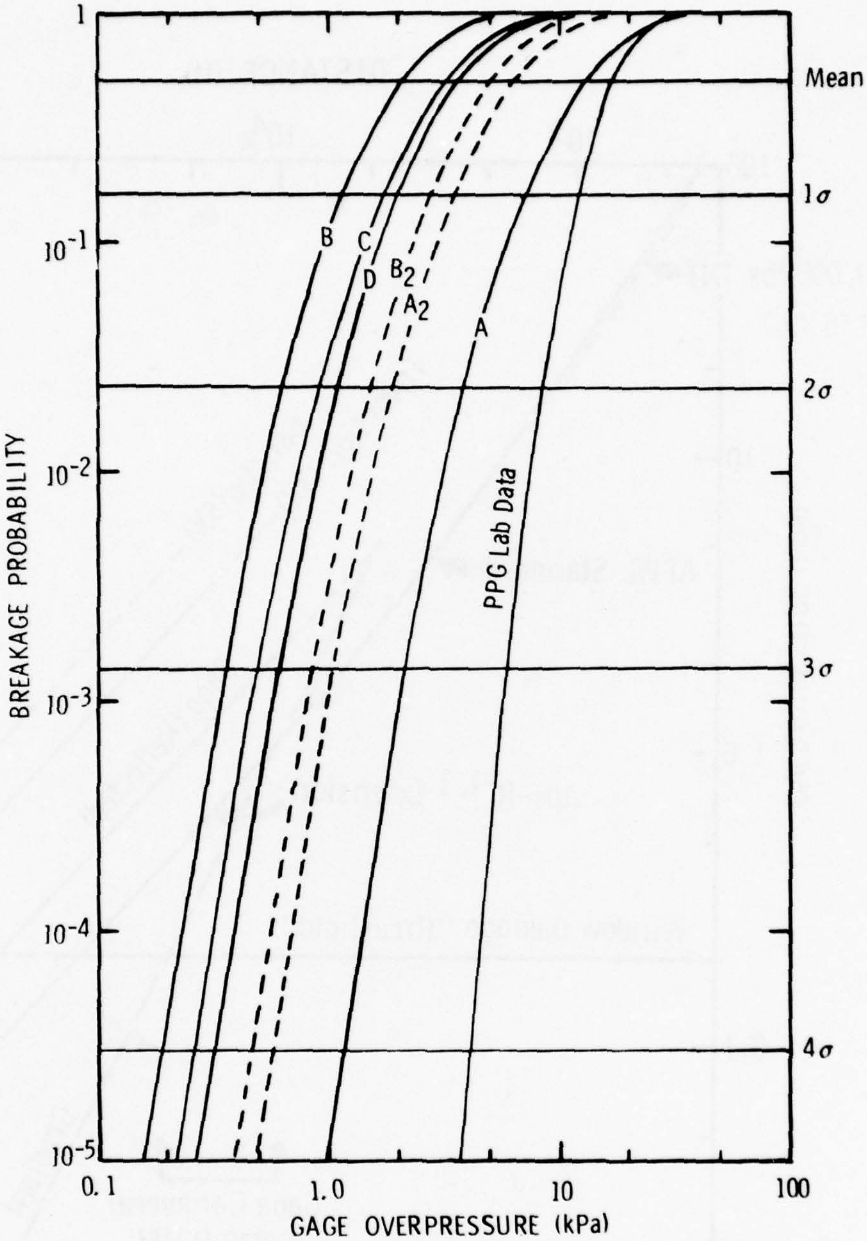


Figure 3. GLASS BREAKAGE PROBABILITY VERSUS AIRBLAST OVERPRESSURE

SQUARE WINDOW PANES

PPG Lab Data: 0.09 m^2 2.5 mm Annealed Herculite II

San Antonio Pane Categories:

A 0.09 m^2 2.0 mm SS Common
B 0.56 m^2 2.0 mm SS Common
C 2.32 m^2 6.4 mm Polished Plate
D 4.65 m^2 9.5 mm Polished Plate

Cape Canaveral Special Pane Categories

A_2 0.19 m^2 2.0 mm SS Common
B_2 0.23 m^2 2.0 mm SS Common

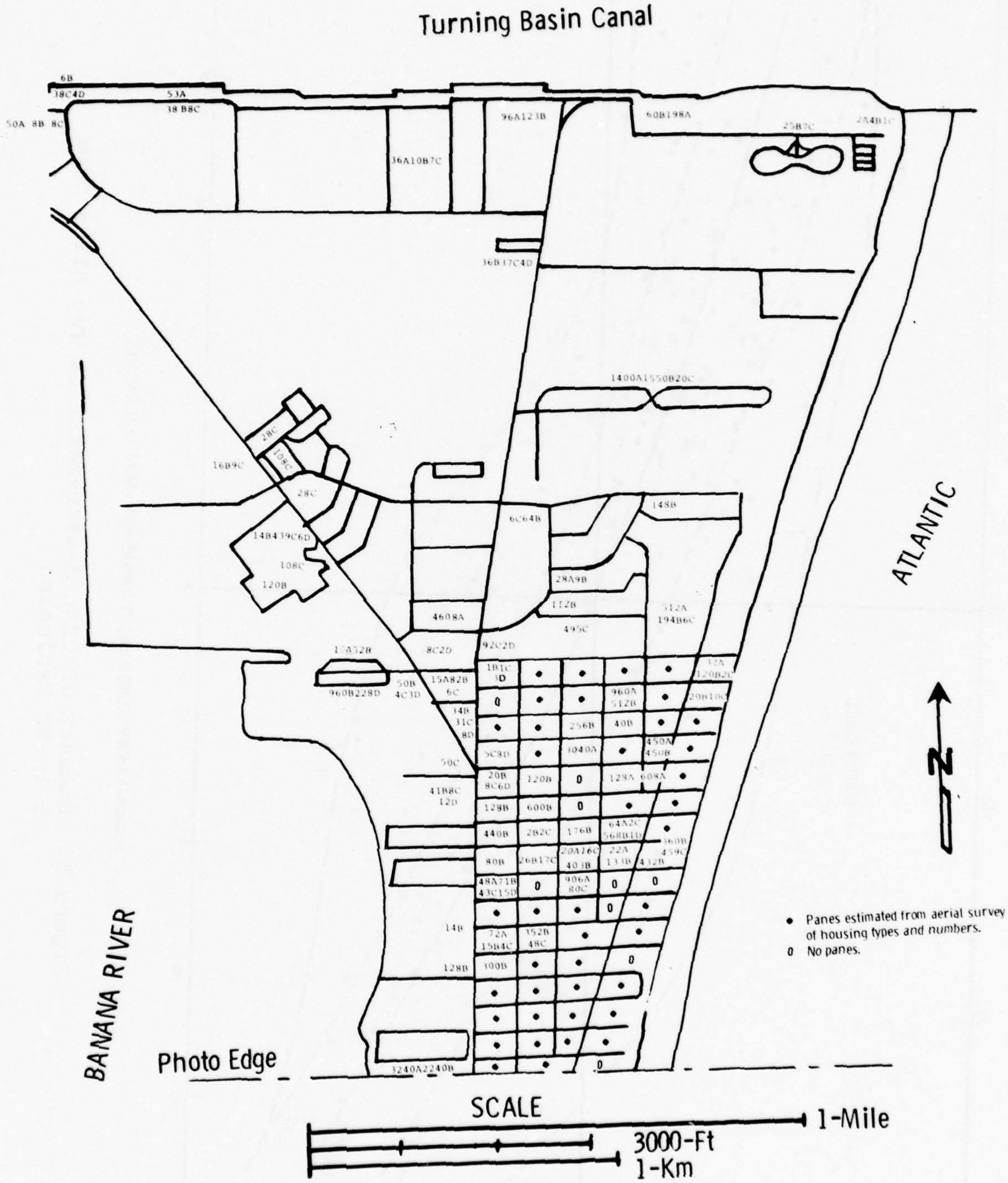


FIGURE 4. CAPE CANAVERAL, FLORIDA
WINDOW SURVEY RESULTS

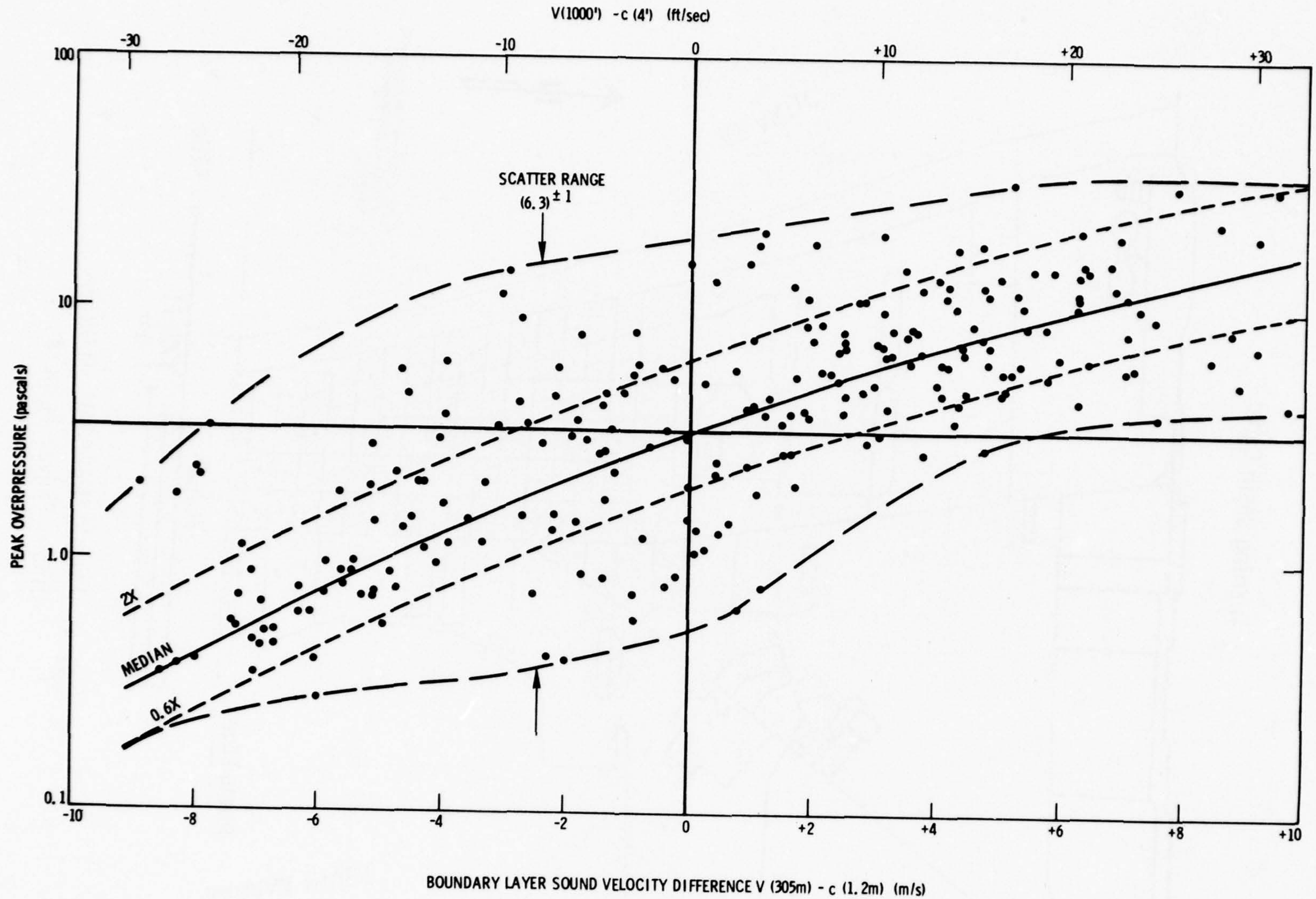


Figure 5. Summary of CERL Measurements at Two Miles from 5 lb HE Explosion

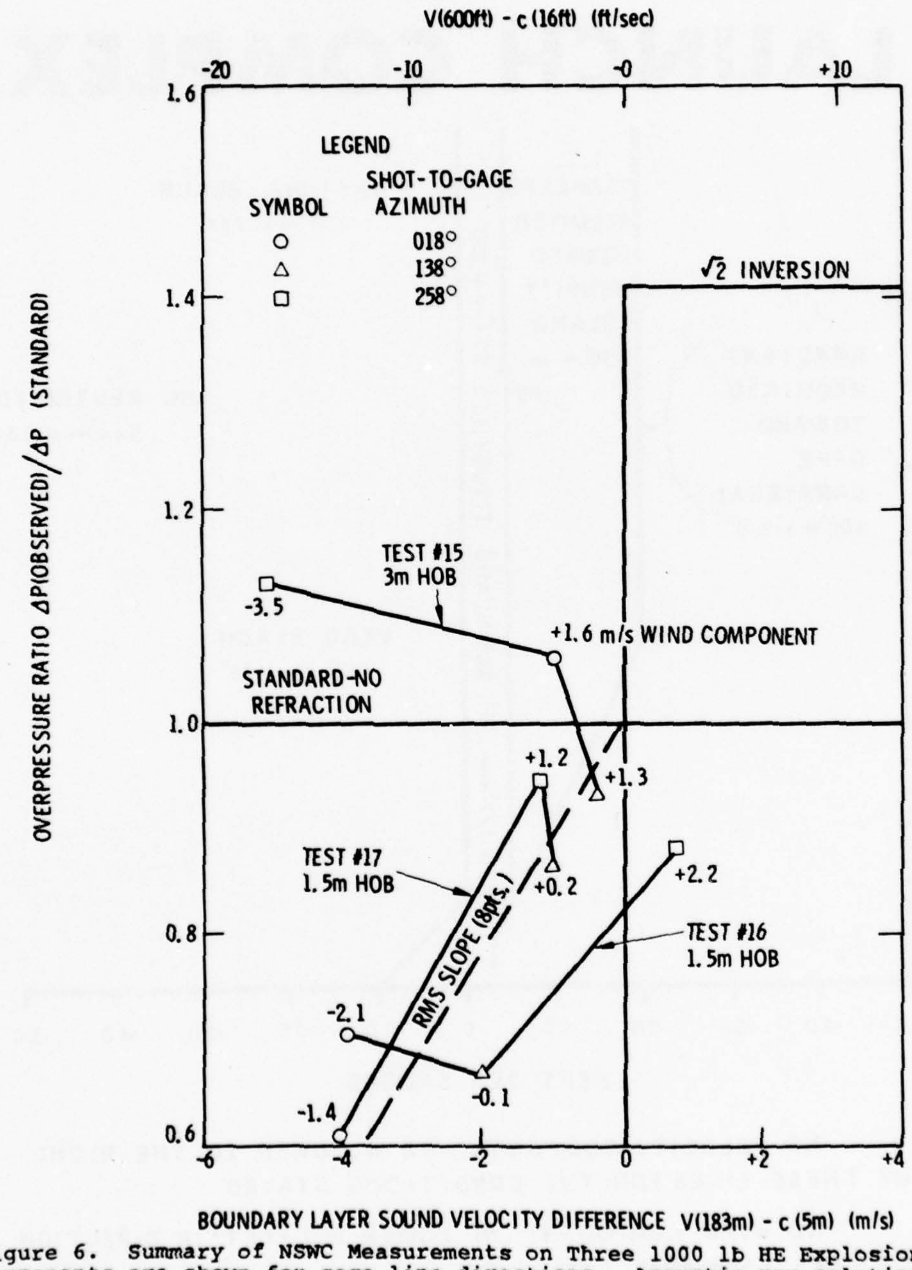
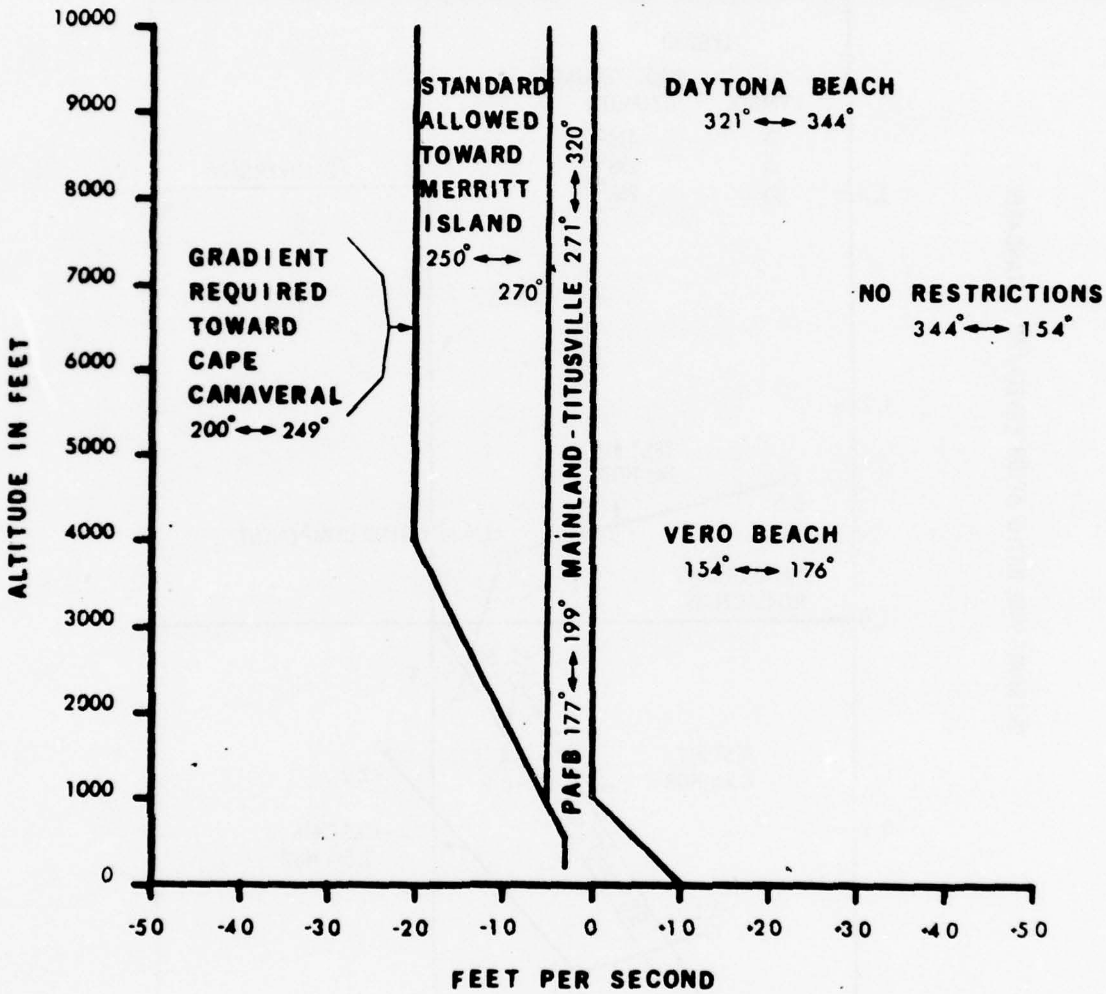


Figure 6. Summary of NSWC Measurements on Three 1000 lb HE Explosions. Wind components are shown for gage line directions. Acoustic ray solutions give magnifications of $\sqrt{2}$ for all inversions (plus differences), 1.0 for radial propagation (zero difference), and zero for gradients (minus differences).

DUCTING CRITERIA FOR LAUNCH COMPLEX 25



NO VELOCITY COMPONENT IS ALLOWED TO THE RIGHT OF THESE LINES FOR THE CONDITIONS STATED

NO WIND COMPONENT IN LOWER 200 FEET IN DIRECTION OF CAPE CANAVERAL. (200° – 240°)

FIGURE 7

EFFECTIVE: 23FEB77

MECHANISMS FOR WAVEFORM PECULIARITIES IN UNDERWATER SHOCKS FROM EXPLOSIONS IN AIR

by

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NAVAL SURFACE WEAPONS CENTER
SILVER SPRING, MD

Shock waves from explosions in "free" air or "free" water are generally uncomplicated and their characteristics well known. Explosions near a water/air interface present a more complicated situation. The resultant transmitted shock waves are generally complex, whether they are those in air due to an underwater explosion or those in water due to an explosion in air. The water-to-air transmission problem has been investigated and the results documented.[1,2] Investigation of the air-to-water problem is underway. This investigation has revealed the extremely complex nature of the underwater shock waves generated in the air-to-water transmission situation. In this paper some of the underwater shock waveforms are described and the mechanisms of their formation are discussed.

The explosive charges are segmented cylinders made to model a missile. They weigh about 3.63 Kg. However, the data for a solid cylinder are not greatly different from that which I will show. Therefore, my remarks will also apply to cylindrical charge data where the length to diameter ratio of the cylinder is about 3·7:1.

The experimental setup is shown in Figure (1). The charge is suspended at the desired height of burst (HOB) above the water surface. An underwater blast gage array was installed below the water surface. Gage positions are given in terms of horizontal range, R, and depth below the water surface, D.

The underwater shock waveforms shown in Figure (2) are from the original oscilloscope records. Records from replicate shots are traced over one another. The waveforms

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1 Rudlin, L., "Measurements of the Airblast from the Underwater Explosion of TNT Spheres," U.S. Naval Ordnance Laboratory NAVORD Report 3913, 30 June 1955.

2 Pittman, J., "Characteristics of the Airblast Field Above Shallow Underwater Explosions," U.S. Naval Ordnance Laboratory NAVORD Report 6106, Dec 1958.

shown in Figure (2) are characterized by multiple pressure peaks and by uncertain decay constants. Some of the peaks are reproducible and some occur randomly.

A general observation is that as HOB increases from 0.28m to 1.16m in Figure (3), the waveforms become more complex. However, at the highest HOB, 2.44m, the waveforms contain fewer random pressure pulses. This pattern emerged throughout the investigation. If the burst height were great enough or small enough, the underwater shock waves were reasonably uncomplicated. However, at the middle HOB, the waveforms were made up mostly of randomly occurring pressure pulses. An explanation for the above behavior is suggested here. Although we are primarily interested in cylindrical explosions, our explanations will touch on spherical explosions since much of what we say applies to both.[3] It is the air shock reflecting off the air-water interface that drives the underwater shock. When the explosion occurs near the water surface, momentum from the explosion products is also transferred to the water. The area at the water surface where significant blast wave transfer occurs is quite small for a spherical explosion, probably limited to the region of regular reflection. For the cylindrical explosion the area may be even smaller. Here the explosion products and their air shocks off the end of the cylinder drive the underwater shock (Figure(4)). However, at the lowest burst heights, the air shock off the sides of the cylinder may also contribute to the underwater blast wave. The air shock in the early stages of the expansion is essentially attached to the explosion products front. (Figure (4)). Thus the airshock will have the contour of the front. As the front expands it slows down rapidly and the airshock detaches, moves out ahead and begins to "heal"; i.e., it begins to smooth out. If the charge is high enough, the healing process is well underway by the time it reflects off the water surface and the water surface is hit by a relatively smooth airblast wave resulting in a reasonably clean underwater shock wave.

When the charge is very close to the water surface, the instabilities on the explosion products front are closely spaced in distance and time so that the water surface is again hit with a relatively smooth airshock and explosion products front. This, coupled with some healing of the underwater shock and the finite high frequency response of the underwater gages, results in relatively smooth underwater shock waves.

[3] Miller, L., et al., "Water Shock Waves Resulting from Explosions above an Air-Water Interface", Report #1-771, Waterways Experiment Station, Vicksburg, Miss.

Detonation at some intermediate burst height creates the worst situation. Instabilities on the explosion products have grown enough to present a multiple and measurable source. Yet, the downward velocity of the front is still very high. Thus, the explosion products and their bow shocks strike the water surface in a random space-time regime. In so doing they act as a multiple source for the underwater shock wave.

Reproducible pulses fall into two categories. The first types are very small and have little effect on the overall shock wave. An example of these are shown in Figure (5) and occur at about 100 μseconds on the trace shown for R=1.22 meters and D=1.22 meters. Such perturbations may be reflections from gage supports or other structures, but are insignificant in the light of other pressure excursions.

Pressure peaks containing significant amounts of energy are of interest. Note in Figure (2) for the columns of gages at R=1.22, the underwater waveforms show two distinct pressure pulses that converge to a single pulse at the deepest gage position where D=2.44 meters. For gages in the two columns further out where R=3.66 meters, pulse separation increases and the two pulses do not coalesce even at the deepest gage.

The arrival times of the second pulses in Figure (2) place their origin near surface zero and their propagation paths entirely through water. The first pulse arrives earlier via a "least-time" path through air and water. The arrival time for this pulse may be calculated with the aid of Figure (6). Note that the first pulse travels through air to a point on the water surface that is R-x from surface zero. It then travels a distance underwater $\sqrt{x^2+D^2}$. Knowing the value of x we find A_t, the arrival time of the first pulse at the underwater gage as the sum of the travel time in air, T_A, and the travel time in water, T_W, ($A_t=T_A+T_W$). The arrival time of the airblast wave front at points along the water surface is given below.

$$T_A = C_1 + C_2(R-x) + C_3(R-x)^2 \qquad (1)$$

C_1, C_2, and C_3 are empirical constants and R and x are defined in Figure (6). Pressures transmitted underwater

are reasonably low so that the underwater shock velocity, V_W, is determined empirically. Therefore:

$$T_W = \frac{\sqrt{R^2+x^2}}{V_W} \tag{2}$$

From the above:

$$A_t = C_1 + C_2(R-x) + C_3(R-x)^2 + \frac{(R^2+x^2)^{1/2}}{V_W} \tag{3}$$

We find the value of x such that A_t is a minimum by differentiating equation (3) with respect to x. Then set

$$\frac{dA_t}{dx} = 0.$$

and solve for x.

Using the above method, we calculated first pulse arrival times for the conditions below:

Charge weight = 3.63 Kg
HOB = 0.28 m

C_1, C_2, C_3 in equation (3) = 57.76, 71.44, and 182.97 respectively.

$V_W = 1.11\Delta P + 1482.8$ (Meters/second)
(ΔP = underwater shock wave pressure in second peak in MP_a. The V_W used here was approximately 1493 meters/second)

Calculated and measured first pulse arrival times for three gage positions are compared below.

Horizontal Range (M)	Gage Depth (M)	First Pulse Arrival Time (ysec) Calculated	Measured
3.66	1.22	2244	2174
1.22	1.22	1083	1061
2.44	2.44	2208	2190

The two-pulsed characteristic of the underwater shock wave obtains for other burst heights as well as for spherical charge data.[3]

This paper has attempted to explain some of the pecularities on airblast induced underwater shock waves. Other phenomena that affect air-to-water blast wave transfer include mach stem formation in the airblast reflection process. Another factor is surface roughness of the interface,wind waves. No attempt was made to correlate specific underwater shock wave pulses with such phenomena.

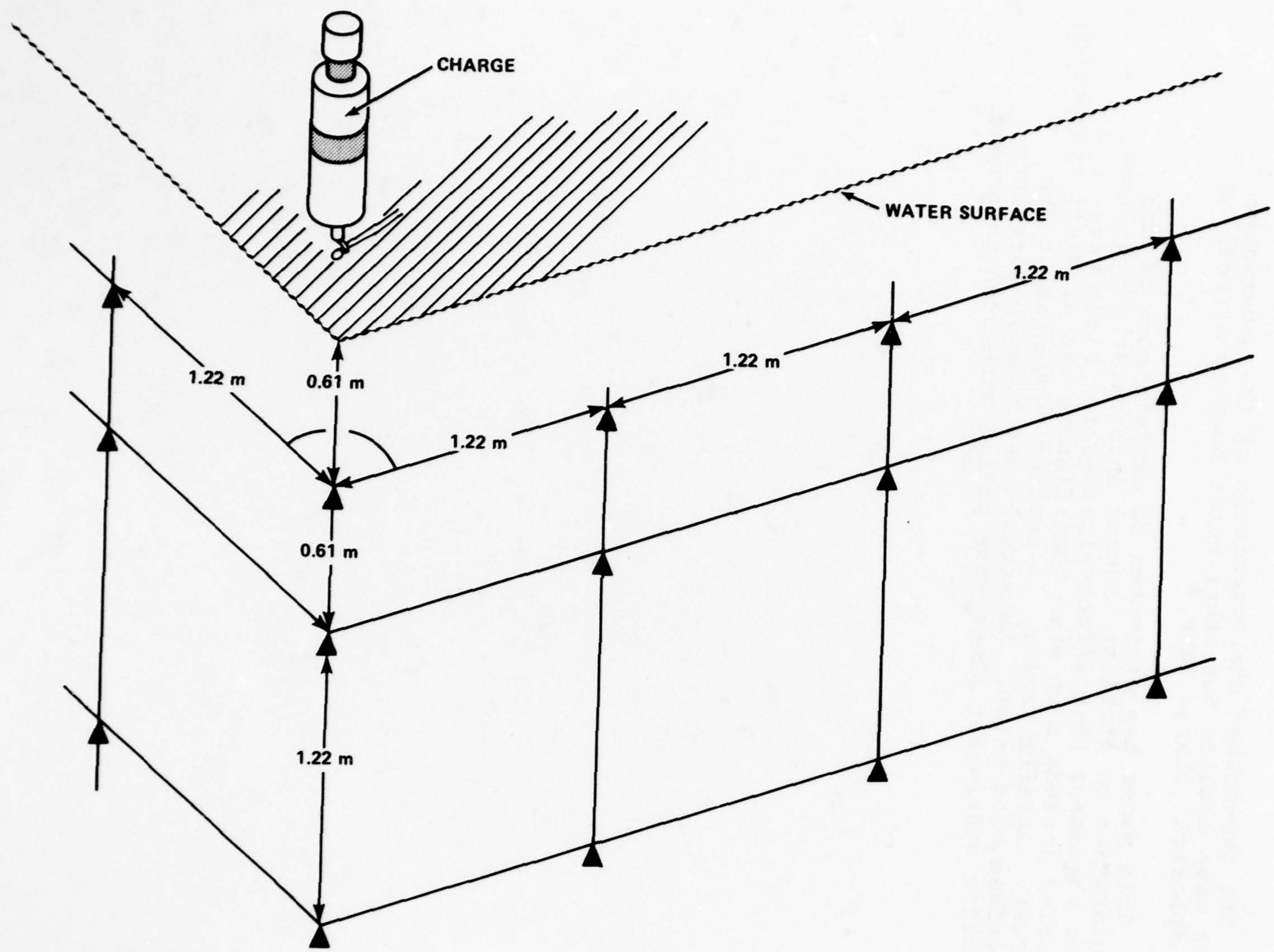


FIGURE 1 GAGE ARRANGEMENT

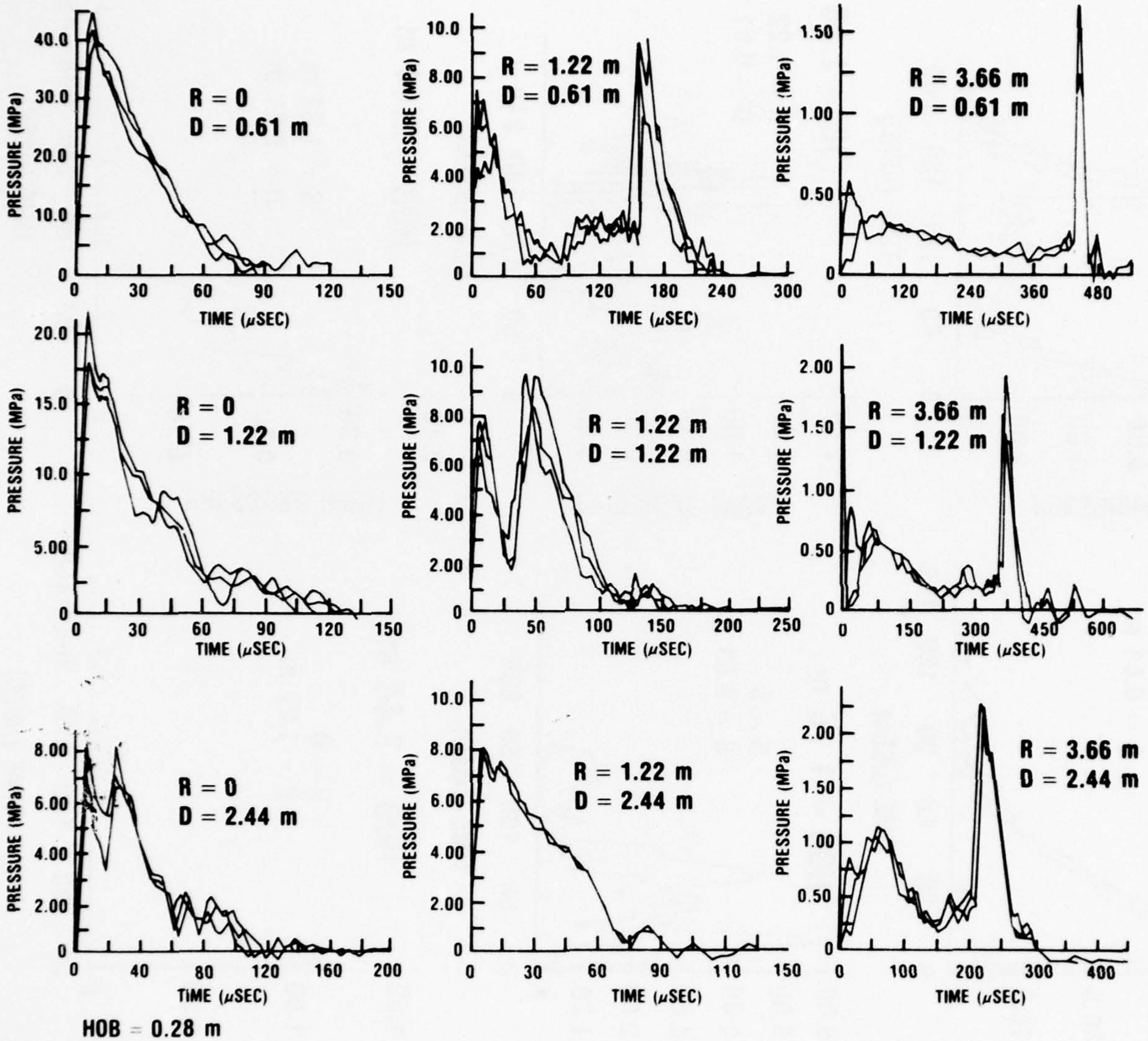


FIGURE 2 UNDERWATER PRESSURE-TIME HISTORIES; 3.63 kg CYLINDER, HOB=28 cm

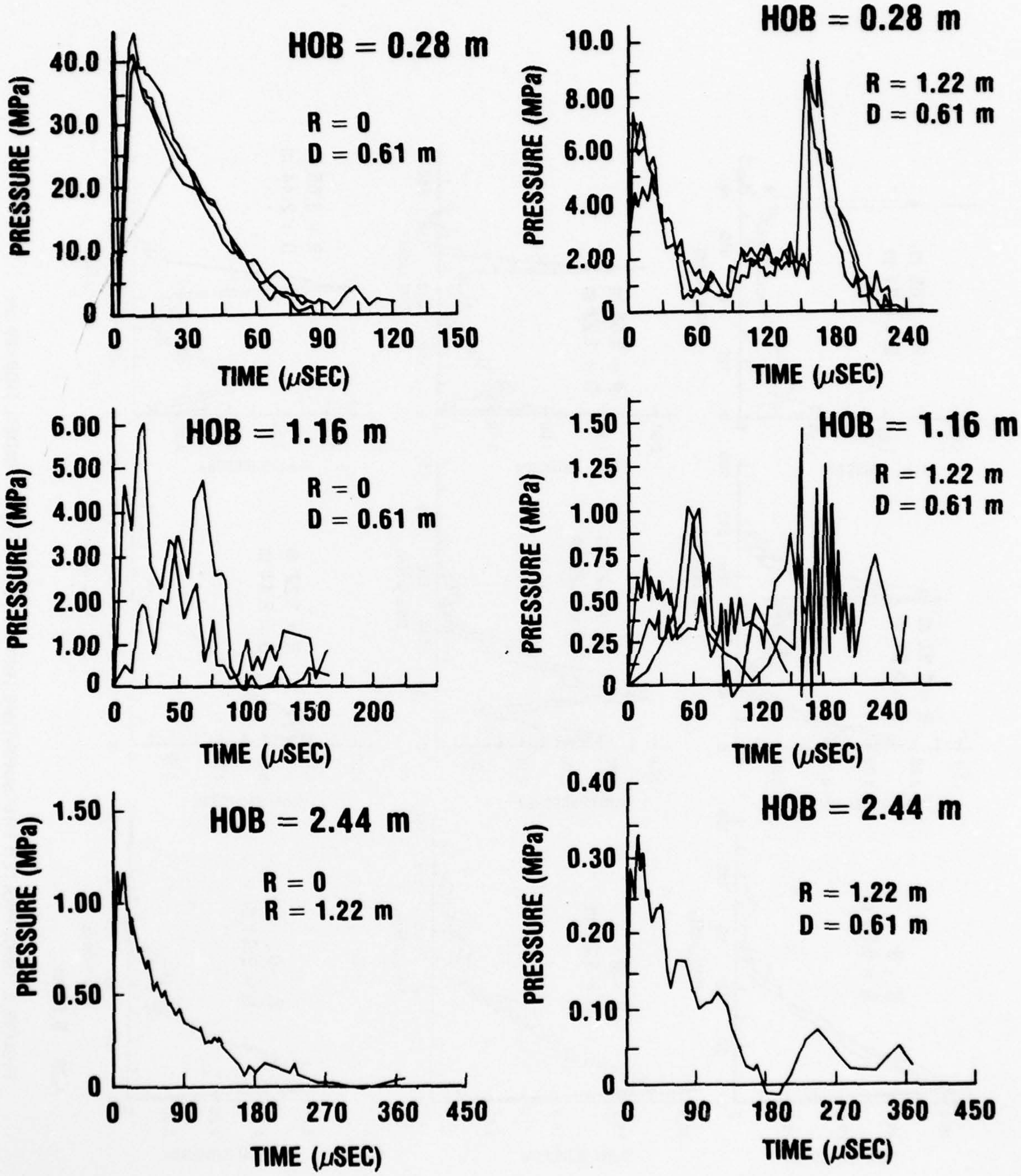
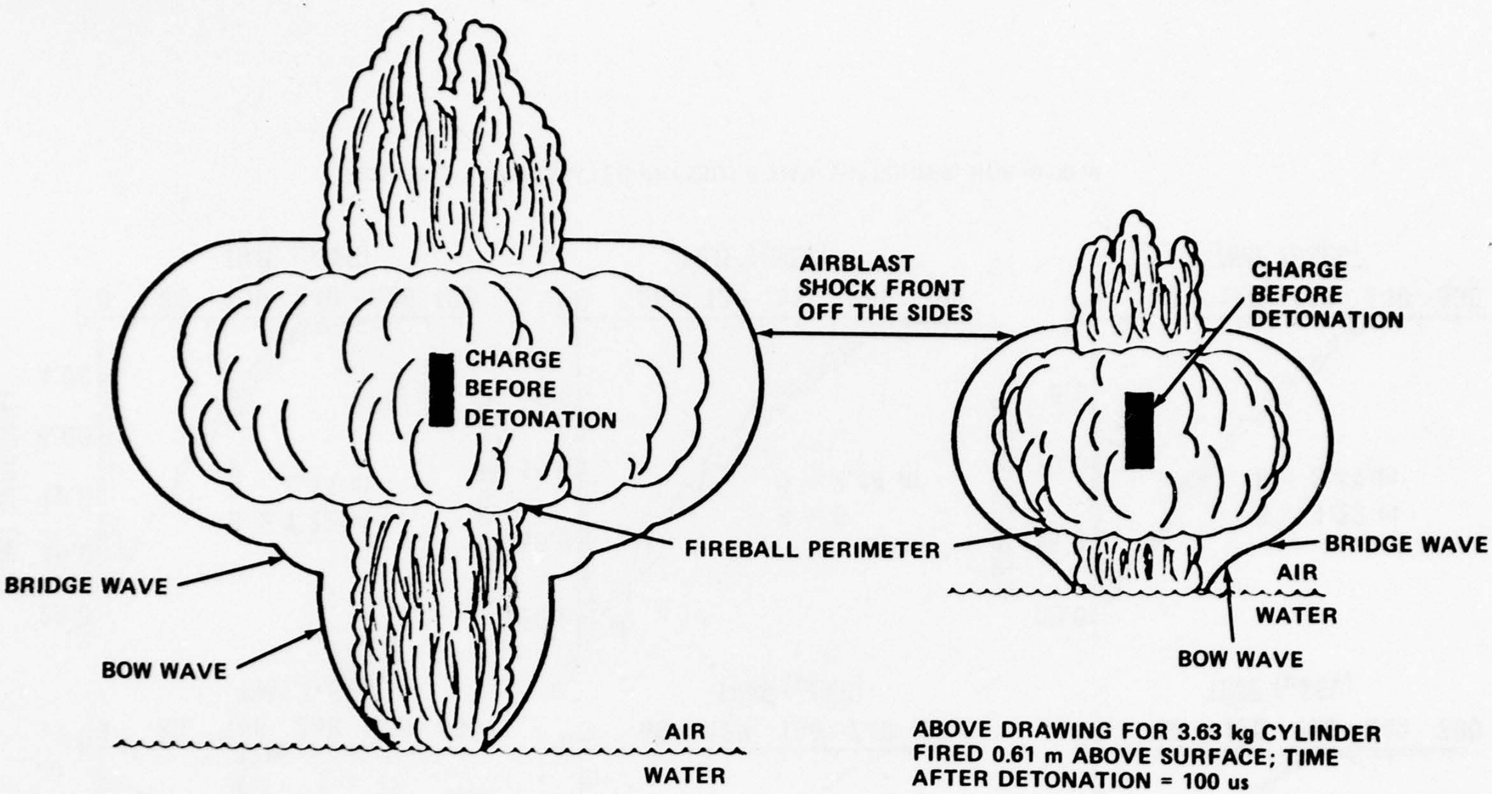


FIGURE 3 UNDERWATER PRESSURE-TIME HISTORIES; 3.63 kg CYLINDERS EFFECT OF BURST HEIGHT



ABOVE DRAWING FOR 3.63 kg CYLINDER FIRED 1.5 m ABOVE SURFACE; TIME AFTER DETONATION = 360 us

ABOVE DRAWING FOR 3.63 kg CYLINDER FIRED 0.61 m ABOVE SURFACE; TIME AFTER DETONATION = 100 us

FIGURE 4 FIREBALL-SHOCKWAVE RELATION FOR CYLINDRICAL CHARGE FIRED IN AIR NEAR A WATER SURFACE

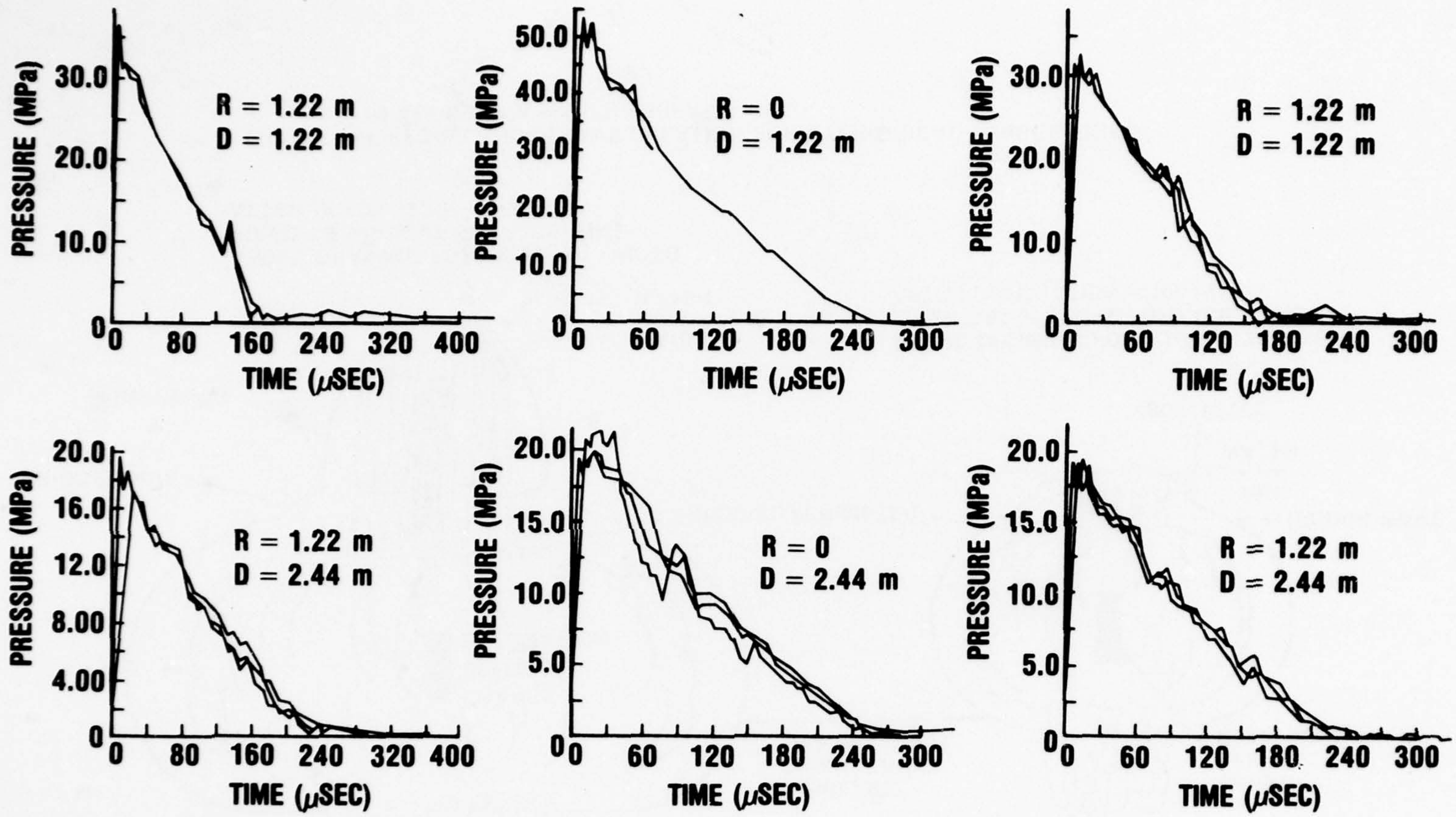


FIGURE 5 UNDERWATER PRESSURE-TIME HISTORIES; HOB=0.00 m

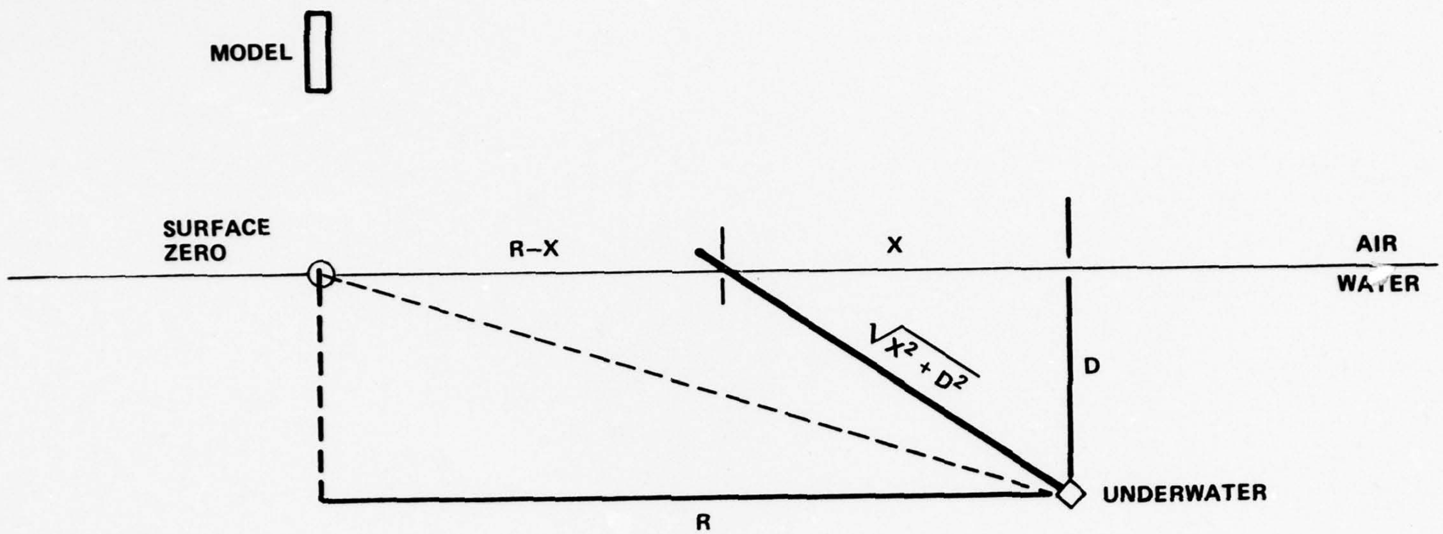


FIGURE 6 SHOCK PROPAGATION PATHS

THE UK ORDNANCE BOARD

ORDNANCE BOARD SAFETY GUIDELINES FOR MUNITIONS

Major General John Hamilton-Jones
Vice President, Ordnance Board
United Kingdom

Publication Issue

The technical publication about which I am to speak has had a long and painful birth for reasons that will become apparent as I unfold the story. It is in late draft form now and it is expected to be published as a UK Defence Standard early in 1979. If after I have spoken you are interested in obtaining a copy I suggest you write to me at The Ordnance Board.

Introduction

Before describing the Manual I should sketch in the background and I start by telling you something of the Ordnance Board itself, its role, function and responsibility.

Origin of Board

The Board traces its origin back as far as 1414 in Henry V's reign and until early in the 19th Century was a power in the land, the Master General of the Ordnance having a seat in the Cabinet. The Duke of Wellington, no less, was one of the last of these Soldier/Statesmen before he became Prime Minister. In 1858, however, the original powerful Ordnance Board was abolished, giving way to a series of Ordnance Committees - until 1939, when the Ordnance Board as we know it today was established. The roles of the Master General of the Ordnance and the Board diverged in the Middle of the last Century and have remained apart ever since.

Present Organisation

The Board now has as its head a President with 2 Vice Presidents who are the Senior Members of their SERVICES. These three, normally of 2 star rank, are supported by the Secretary and 13 Members from the 3 UK armed services and the Scientific Civil Service, together with supporting technical staffs.

Terms of Reference

The Board is an inter Service, professionally independent, impartial, advisory body whose terms of reference are given on this slide. Suitability for Service is defined as shown on this slide.

Duties

The Boards Main duties, stemming from the terms of reference are outlined on this next slide.

Appraise To appraise weapon systems containing explosives for safety and suitability for service, having arranged or having been associated with trials on those systems and assessed the results.

Advise To advise Service Staffs and Procurement authorities on matters referred to the Board, particularly where inter-service co-ordination is required. Recommend To make recommendations to Service Staffs on Safety matters affecting the use of weapons during training in peacetime.

Report To report and publish in printed Proceedings:

1. Programme and results of tests and trials.
2. The corporate opinion and recommendations of the Board.

It is important to note that having no executive status, the Board advises and recommends, never instructs.

Direction of the Board

The work of the Board is under the joint functional control of the 3 service Procurement Controllers.

Method of work

The Project Director will seek the Board's advice formally and the task will be placed on the Member of the Board most concerned, each Member being responsible for a particular sphere of the armament field. The assessment by the Member of Safety and Suitability for service will then comprise 4 stages, identified in brief thus:

a. Examining the design of the overall Weapon System the explosives used, the explosive components, the means of ignition, the intrinsic Safety features and establishing conformity with Ordnance Board principles.

b. Establishing the environment, in climatic, chemical, mechanical and electrical terms, which the weapon system, and the explosive element in particular, are expected to withstand in storage, in transport and in operational life.

c. Considering how the intentional means of initiation is protected by the Safety features, taking into account development trials. Determining the trials programme and arranging it.

d. Monitoring the trials, analysing results, reviewing the evidence, forming conclusions and submitting a draft Proceeding with appropriate recommendations for the approval of the Board.

Proceedings

The Board will make its corporate decision known to the approving authority by means of a Proceeding, and it will be appreciated that as the years go past, a large number of Proceedings comprise the written record of Board decisions. Some of these will, of course, be ephemeral in the sense that the weapon or component which was the subject of assessment has been discarded, the bulk are related to weapon systems which in course of time have become obsolete, the most recent are extant and will remain of continuing interest while the Weapons to which they relate remain in Service. To give the scale of this enterprise I should interject here that the Current Proceeding now being submitted to the Board is numbered 41952. All, however, are grist to the mill of experience and historical record and are the foundation stones, as it were, of the principles which have evolved and have been formulated over the years. These principles are codified in a number of important Proceedings and these have been used in the preparation of the Manual which I now propose to describe to you.

Origin of the Manual

It had long been recognized that it would fulfill an ever increasing need if the cardinal principles governing weapon safety were to be collected within the covers of the publication. It was not until eighteen months ago that this need crystallized into a positive task which was placed on the Naval Vice President. Accordingly, he organized a small editorial committee under his chairmanship which set about the compilation of the Manual which has been entitled

"Ordnance Board Safety Guidelines for Munitions".

<u>The Need for the Manual</u>

The need for the Manual had become the more urgent on account of a number of factors, the more important of which were the appointment of firms in private industry as Prime Contractors for the development of weapon systems, the generation by Government of Health and Safety at Work legislation that affects defence, the increase in foreign weapon purchase, the increase in international Collaboration involving some acceptance or recognition of foreign procedures, the retirement of the last generation of Senior officers with war experience, the increasing complexity of weapon systems and the growing lethality of explosives. I should interject here that the manual does not touch upon Nuclear Weapons which are specifically excluded from the content. Apart from the factors mentioned it was concluded also that because of organisational changes in the three services, officers appointed to the Board whether as Members or as Technical Officers were in some cases unfamiliar with proven concepts and the philosophies so painstakingly generated in the past. So it was that, not before time, positive action was taken to prepare the publication and to define its content.

<u>The Title</u>

The title itself needs perhaps a passing explanation. The Ordnance Board as I have tried to explain has no executive status and expresses its corporate recommendations to the approving authority as advice, and it is for that reason that the Manual sets out "Guidelines" as opposed to instructions or commands. As for the term "Munitions", the variety of the stores, comprehended in the term ranges from simple ignition devices such as match heads through the whole index of weapon systems and ammunition deployed by, or destined for, the armed services, to the complexities of fuzing systems and the explosive components of missiles, torpedoes and bombs.

<u>Justification for the Manual</u>

A large number of Proceedings and other documents cover this field so that it is difficult for Weapon designers, project managements and officers of the Board to grasp the totality of the information provided.

So the Manual aims to bring together these general principles into a form convenient for use and easy reference and by so doing provide a reasonably comprehensive review of the whole field of Weapon design Safety.

Contents of the Manual

The next slides indicate the content of the Manual and, leaving you to read the Chapter headings, I will merely highlight those chapters which I wish to mention in this brief summary:

Chapter 1 - Safety Philosophy
Chapter 15 - Safety of Warheads
Chapter 19 - Life Assessment
Chapter 20 - Environmental Testing
Annex C - Examples of Accidents and their causes

Chapter 1

This Chapter attempts to set the scene for the ensuing Chapters by bringing out for appraisal the underlying philosophy. It explains the fundamental paradox - the aim of developing a lethal device while endeavouring to ensure that it is safe and invulnerable to the environment until the moment of "delivery", and the chapter argues that the nature of explosive propellants and pyrotechnics demands special care and the need, therefore, to tap experience and apply proven concepts to the design of safety features, Such considerations are especially germane in the sense that designers are often working on the frontiers of technology. New weapons will normally be conceived as improvements on their predecessors and are likely to be required to face more severe conditions and to provide a more energetic output. It is stating the obvious to emphasise the importance during development of identifying and rectifying weaknesses and positively confirming safety by careful assessment, for the reason that accidents in service erode morale and can attract crippling penalities in time and cost. This Chapter begins with a truism which all of us well understand but which is forgotten at our's (or preferably someone else's) peril. "If it is possible for an accident to occur then at some time it will do so".

There is, however, no guarantee of absolute safety and a safety assessment must be conducted with a fine sense of balance between the precautions thought advisable and the possibility of over-complication and lack of operational readiness, to achieve an acceptable level of Safety and reliability.

The question of level of acceptability is contentious and difficult to determine because of its subjectivity and the influence of current technological progress in every field. We have all come to accept some degree of risk in our daily lives - a practical difficulty lies in the definition of a satisfactory means of demonstrating with a high degree of confidence that an acceptable safety level has been achieved. The Chapter concludes that it is the responsibility of the Project Management to weigh the cost of accepting risks or reducing them wherever possible against those which may be incurred by the potential hazards and advising the user accordingly. In making the assessments which contribute to this judgement, the Board examines the design of the explosive store, taking into account the environment in which it is transported, stored and operated and the application of existing principles and guidelines which the Manual seeks to advance. Once design standards have been agreed the Board bases its further assessments of safety and suitability for service upon the results of the programme of selected environmental tests.

Chapter 8 Safety of Fusing Systems

There is little to be added to the principles set out currently in Proc 41754 and which are widely known and recognised and are indeed published as UK Defence Standards - although the Defence Standards inevitably lag behind the amendments which are made to the principles by the Board. The latest amendment adapts the principles to apply to Electronic Safety and Arming Systems. A Board Study Group into the reliability, Safety and Suitability for service of electronic Safety and Arming systems rendered a report which was published as a Proceeding and this is reproduced under Chapter 14.

Chapter 15 Safety of Warheads

Together with Chapter 10 "Safety of tube launched Projectiles", this Chapter attempts to encompass the Board's views on the safety requirements for explosive containers. There are Chapters respectively on the explosive itself and the means by which a safety assessment is achieved, and, again, on compatibility of materials with explosives, Chapter 15 on Warheads bring out the factors which are taken into account when approved explosives are used in a weapon application e.g. the configuration of the warhead and its strength characteristics, the need or otherwise of the explosive to provide physical support to the warhead structure, the means of filling the explosives, the consequences of adverse climatic conditions and the nature and sensitivity of any exudate. Cleanliness, purity of filling, internal surface finish, re-entrant angles, welds are also discussed.

Chapter 19 Life Assessment

This is a subject which always seems to strike a resonant chord in Board debates. Storage, operational and service lives are defined and the Board's philosophy on life assessment, their approach to accelerated climatic trials, simulated real life trials and diurnal temperature cycles are argued and summarised.

Chapter 20

A subject closely associated with Life Assessment is, of course, that of Environmental trials. This Chapter discusses the formulation of environmental trials, but first it stresses the need for an accurate and comprehensive statement of the environment the Munition is likely to experience throughout its life. The Board acquires this knowledge by means of an Environmental Questionnaire which is answered by the Project. Only with this knowledge is it possible to frame a sensible schedule of trials to demonstrate that the Munition will withstand induced environment, such as handling, transport, air carriage and so forth or the natural environment of temperature, humidity and pressure. The Chapter sets out the several considerations which should govern the formulation of the trials and discusses the forms of accelerated testing, sequential tests, and functioning.

Risk or Danger

A final Chapter philosophises on risks and hazards. Emerson wrote "as soon as there is life, there is danger" and it is true that risk or danger begin even before we are born. Birth itself is hazardous and all nations quote death rates in these early months as so many per thousand. The developed nations strive through education, clinical techniques and accident prevention doctrines to reduce the mortality rate. Similarly they attempt to reduce the death rate among adults by the promotion of road safety programmes and the like. As a result an increasing proportion of those born reach the biblical norm of 3 score and ten despite the novel dangers which civilization has introduced. Most personnel in the armed forces, as well as civilians engaged in the development, manufacture and storage and transport of munitions, work and often live in what may be termed an "explosive environment". They are still exposed to all the hazards of everyday life but they face a superimposed additional risk. It is right that this additional risk should not seriously reduce these people's chances of survival to old age. At present fatal injuries due to accidents involving explosives amount to an insignificant proportion of those from other causes. Such a state of affairs is arrived at after the expenditure of a great deal of time and money and much more would need to be spent if the accident rate were to be reduced further. How far is it sensible to go? The answer is a political one and is not answered in the Manual, but a few of the arguments are touched upon in the final Chapter.

The Annexes

There follows a number of Annexes - Terms of Reference of the Board which I mentioned in my introduction - an account of the activities of the Explosive Safety and Transport Committee, which is collocated with the Board and of which I am Chairman. There are two other Annexes : one which relates to the Acceptance and Approval procedures

in UK, which I think have minimal interest to those other than UK readers, but the final one is salutary for it contains brief accounts of some major accidents which have occurred in UK and which were attributed to a design shortcoming. Most accidents involving weapons and ammunition are caused by human errors, poor workmanship or bad drill; mal assembly is another source of error, but a safe design should have precluded the possibility of the mal assembly of a critical feature.

The Portsmouth and Gibraltar explosions were similar in that both incidents originated with low order handling shock acting on a local point of super-sensitivity within the filling of a particular type of depth charge causing ignition. 2 cements using excessive Napthan solvent had created the conditions in which ignition could be started in Torpex filling. Elimination of the cements and substitution by compatible compounds prevented a recurrence. There are accounts also of an incident at an RAF Station causing the death of 2 aircraftmen when an 18" MK30 torpedo (now obsolete) exploded under test. That accident was attributed to lack of insulation of a pistol pocket lead. There are accounts also of gun prematures. These dismal reports are included as much to dispel myth and legend as to point a moral.

Finale

That concludes my summary of the Safety Guidelines and I show the contents again to remind you that I have only touched on a small part of the whole. The Board is well aware that the Manual is only a beginning and is only likely to achieve its full potential after a year or two of use in the field and we have every intention to respond to feed back.

By the time it is published as a Defence Standard it will have had the imprimatur of the Board as a corporate body. It is right and proper that before publication the painstaking process of bringing the Manual, Chapter by Chapter, before the Board for approval is maintained. While the Board takes full responsibility for the content

you may be reassured to learn that we have taken the precaution of obtaining a wide measure of support from those engaged in Munitions procurement in UK. The Board is confident that the publication will promote the safety of every sailor, soldier, airman and civilian who may be involved in or affected by the handling, storage or functioning of explosive stores.

(Proverbs 11 : 14)

Where no counsel is, the people fall : but in the multitude of counsellors there is safety .... and not only for the counsellors!

BLAST AND FRAGMENT CONTAINMENT CAPABILITY OF PORTABLE CHAMBERS*

by

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and

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ABSTRACT

This paper is primarily concerned with the development of new technology for the safe transport of armed explosive devices by explosive ordnance disposal units. The results of research to determine the blast containment capability of 2-ft diameter, 0.5-in. wall spherical vessels will be presented together with the use of a simple means to prevent fragment damage to the vessel from steel encased explosive charges. Fragment cratering damage is prevented through use of a relatively thin annulus of non-fragment producing mass such as sand or plaster of Paris.

It was found that a 2-in. annulus of sand surrounding a C-4 filled, 2-in. diameter pipe was sufficient to prevent the formation of fragment craters on the inside of a chamber for the complete containment of the blast and fragments from an explosion. This fragment restraint system was demonstrated in a series of explosive tests in a 2-ft-diam., 0.5-in. wall spherical blast containment chamber designed and fabricated for this investigation. It was also found that bare cylindrical charge shapes lead to greater local strains in a spherical vessel in the plane normal to the charge axis than equal weight spherical charges, while the metal and sand encased charges produced even greater plastic deformation of the containment vessel. The complete results of the fragment restraint studies and of a series of ten explosive containment experimental shots are given. An analytical model for the elastic-plastic deformation of the chamber shows good agreement with the observations for the bare spherical charges fired in the chamber.

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* Sponsored by the U. S. Naval Explosive Ordnance Disposal Facility, Indian Head, Maryland, under Contract No. N00174-74-C-0219.

INTRODUCTION

Since 1971, Battelle's Columbus Laboratories have been developing the design criteria for lightweight, portable (or transportable), completely-enclosed blast containment chambers for explosive ordnance disposal (EOD) applications.[1-3] Good correlations were found between the one-dimensional, thin-walled solutions[4] to the equations of motion for elastic and bilinear elastic-plastic constitutive relations and experiments using bare compact[1] or spherical[5,6] explosive charges in spherical chambers. This paper describes research[7] sponsored by the Naval Explosives Ordnance Disposal Facility, Indian Head, Maryland, which was directed toward initial investigations in three technical areas that could extend the usefulness of portable blast containment chamber concepts.[8] First a lightweight disposable system was needed to prevent the production of craters in the interior of containment chambers from metal fragment producing explosive devices, especially pipe bombs. This was necessary to prevent the premature failure of the entire chamber due to the production of flaws exceeding the critical flaw size for propagating fracture.[9-11] Second, experimental results on the effects of the use of a fragmenting device (pipe bomb) with the fragment restraint system on a small (2-ft-diameter) portable blast containment chamber were desired. Third, for comparison purposes the effects of long cylindrical bare explosive charges on the portable chamber were needed. This paper describes these investigations and the results obtained. The paper is divided into three main sections, which describe the fragment restraint system*, the design of the portable chamber, and the experimental explosive firings in the portable chamber. Additional photographs and engineering details are given in Reference 7.

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* A paper on two subsequent projects to develop and understand fragment restraint technology[12-13] has been presented during the "Suppression of Fragments and Blast" session of this Seminar.

FRAGMENT RESTRAINT SYSTEM

Rather than the provision of disposable armor on the vessel interior, the approach taken was the provision of additional mass of non-fragment producing material surrounding the metal-cased explosive charge, as suggested by Mr. Lennard J. Wolfson of the Naval Explosive Ordnance Disposal Facility, the program technical monitor.

To investigate the mass-addition approach a series of eleven experiments were conducted using a 6-in.-length of 2-in.-diameter Schedule 40 steel pipe packed with Composition C-4 explosive and provided with one end cap and additional end restraint at the other end for some experiments. Both common sand and water were tried for the mass-addition surrounding media. The effectiveness of the fragment restraint media was judged by the cratering effects on steel witness plates located near (9-13.5 in.) the charge. Water was soon abandoned because no apparent advantages accrued and the handling difficulties were judged to be a drawback. The radial thickness of the sand barrier was systematically decreased from 4 in. to 2 in. and up to 1-1/4 in. of radial and end-wise air gaps were introduced between the pipe and surrounding sand. The sand was supported in thin, 0.020-in.-thick, soft aluminum containers.

As a control, a bare pipe bomb was fired, which showed that the fragments produced perforated 3/8-in. mild steel witness plates. With the sand surrounding, only a few small marks or dents were observed for the thinner sand annulus experiments. This was a surprising result, because calculations of the velocity predicted for the fragment-sand composite suggested that the residual fragment velocity should still be quite damaging. References 12 and 13 have extended our understanding of the mass-addition fragment restraint system.

Thus, this research showed that a sand annulus surrounding the pipe bomb of manageable thickness (2-2.5 in.) could prevent fragment cratering as desired, and thus was the system used for evaluation in the blast containment chamber. Refer to Reference 7 for additional details.

CHAMBER DESIGN AND FABRICATION

The portable blast containment chamber designed and developed during the present investigation is shown schematically in Figure 1. The chamber had a 2.0-ft inside diameter with a nominal 0.5-in. wall thickness. The single-pin-supported port closure mechanism was a scaled-down and slightly revised version of the design for a larger chamber developed in an earlier program.[1,3,14] The design criteria for the reinforcing ring cross-section and door thickness were basically similar to those developed for the larger vessel. The single-pin door operating mechanism[14] allows the door to be adjusted to a tightly closed inside overlapping position with the aid of the adjusting bolts (see Figure 1). In the open position the door is supported at nearly the same angle as when closed, but is rotated 90 or more degrees around the inside of the chamber to allow free access to the central portion of the chamber through the 12-in.-diameter port. With the aid of the stop

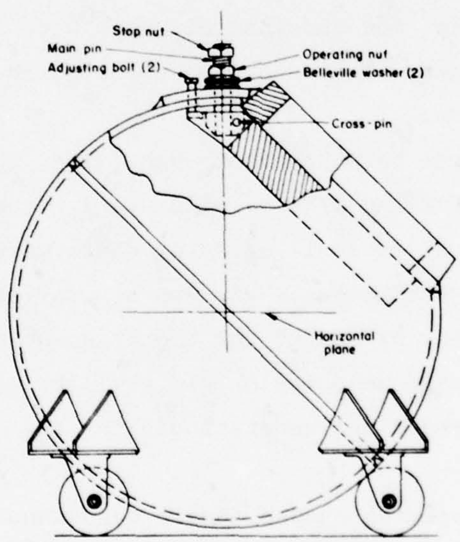

FIGURE 1. SCHEMATIC SIDE VIEW OF SPHERICAL CONTAINMENT VESSEL WITH SINGLE-PIN DOOR SUPPORT MECHANISM

nut locked in position and a door-stop attached to the inner side of the ring (not shown), the door may be closed or opened by the simple rotation of the single operating nut. Operation was eased by a simple handwheel.

The diameter and wall thickness of the chamber were selected to allow easy passage through a standard 30-in. office door and to avoid excessive mass while maintaining the capability to contain a 2-in.-diameter pipe bomb. References 2 and 3 summarize the principles and design criteria for explosion containment vessels that have emerged from the program thus far.

The blast containment chamber was designed to absorb the explosive blast energy by elastic-plastic deformation of the body of the vessel itself.[2,4] Thus, good ductility and toughness to avoid fracture were required, together with the maximum attainable strength within cost and availability guidelines.[11] As no low-operating-temperature requirements were placed on this vessel, the first choice of material was ASTM A-537, class 1 steel. This material was unavailable from the fabricator of the hot-pressed hemispherical heads at the time of this program and an alternate, ASTM A-516, was used for the vessel body instead. This latter material is similar in composition (a low carbon, silicon-manganese steel), elongation, and toughness, but with somewhat lower allowable yield and ultimate strength values. The reinforcing rings and doors were made of ASTM A-537,class 2*, which is similar to the A-537,class 1 material but is somewhat stronger because it is quenched and tempered rather than normalized. Subsequent research[11] has shown that materials of this type are unsuitable for low temperature (-30F) applications due to the ductile-brittle transition they undergo. When low temperature operation is required, HY-80 steel has demonstrated good performance[11,15] and superior strength, at appreciably greater cost, however.

It should be noted that the hot-pressed hemispherical heads utilized for these vessels show a wall-thickness variation of about $\pm$ 13 percent from the average wall thickness, as measured by ultrasonic surveys of the wall thickness. For the present application, this variation does not appear to cause any difficulties.

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* They are similar except for gage. The reinforcing rings and doors were fabricated from a 5-in.-thick plate for availability reasons. The A-537 specification is limited to less than 2-1/2-in. gage.

All welds on the vessel were made following low-hydrogen practice. The main structural welds were multi-pass welds made using a procedure qualified to Section IX, ASME Boiler and Pressure Vessel Code, 1974. Welds were 100 percent radiographically inspected according to Section VIII of the ASME Boiler and Pressure Vessel Code, 1974. It should be emphasized that the highest possible standards for weld quality production and control should be exercised to minimize the possibility of weld failure under the extreme loading conditions expected for these vessels. The complete welding procedures used are given in Reference 7.

EXPLOSIVE CONTAINMENT EXPERIMENTS

A series of ten explosive containment experiments were fired in the two-ft chamber, as shown in Table 1. This series of experiments was designed to make a preliminary investigation of the following variables on the response of a completely closed containment chamber:

- effect of charge weight*
- effect of steel wool as an energy absorber
- effect of a sand layer surrounding an otherwise bare charge
- effect of cylindrical bare charge length-to-diameter (L/D) ratio
- effect of cylindrical pipe bomb L/D with sand fragment restraint.

In these shots the charges were supported at the center of the vessel sphere by stands fabricated from 1-in.-thick Styrofoam of 2-lb-ft^{3} density. The sand layers were supported by Styrofoam and thin cardboard or tape forms. For all non-spherical shots the charges were oriented with the charge axis of symmetry horizontal along the sphere centerline and parallel to the face of the door.

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* Additional destructive testing with bare spherical explosive charges of similar 2.0-ft-diameter vessels was completed in another program and has been reported elsewhere.(1-3) The design limit explosive charge at 60F is between 6.5 and 7.0 lbs with failure apparently due to the static stresses generated by the confined detonation product gas.

TABLE 1. DESCRIPTION OF SHOTS FIRED

Shot Number	Explosive	Explosive Weight	Shape	Housing	Fragment Protection	Energy Absorber
1	C-4	1.59 lb	Sphere 3.71 in. dia.	none	none	none
2	C-4	2.56	Sphere 4.40 in. dia.	none	none	none
3.	C-4	1.52	Sphere 3.71 in. dia.	none	sand[a]	none
4	C-4	2.51	Sphere 4.40 in. dia.	none	none	#2 steel wool 16.9 lb
5	C-4	2.50	Cylinder L/D = 0.89	none	none	none
6	60% Dynamite	1.35[b]	Cylinder L/D = 3.88	8" x 2" pipe[c]	sand[a]	none
7	C-4	1.50	Cylinder L/D = 3.84	none	none	none
8	C-4	1.50	Cylinder L/D = 7.82	none	none	none
9	C-4	1.50	Cylinder L/D = 3.88	8" x 2" pipe[c]	sand[a]	none
10	C-4	1.50	Cylinder L/D = 8.14	13.1" x 1 1/2" pipe[d]	sand[a]	none

Notes: (a) Sand radial thickness 2.5 in. in contact with charge or housing.
(b) Two sticks
(c) Schedule 40 pipe with standard pipe caps on the ends
(d) Schedule 40 pipe with end plugs fitted inside cut from standard pipe caps.

The spherical charges were initiated by detonators imbedded in the center of the charges. The cylindrical charges were initiated by detonators imbedded 1 to 1-1/2-in. in from the end of the charges.

The instrumentation and diagnostics used to evaluate the vessel performance consisted of six strain gages applied to the vessel outer surface and a series of 23 fiducial marks applied to the vessel outer surface. Although valid data on both the dynamic and plastic residual strains were obtained from the strain gages, the data does not add significantly to the results obtained. Thus, we have omitted them here but they are given in detail in Reference 7.

The layout of fiducial marks on the vessel surface is shown in Figure 2. These marks were either fine prick punch marks (on the vessel) or scribed lines (face of reinforcing ring). They were used in pairs to form 16 gage-lengths to follow the progress and distribution of plastic deformation of the vessel. The distance between marks was measured on the vessel surface using point-equipped 12-in. dial-gage calipers with a resolution of 0.001 in. Individual readings were reproducible to at least $\pm$ .005 in. This method of measurement actually measured the chord length between mark pairs, which for uniform spherical strain is a reliable measure of the vessel strain. However,

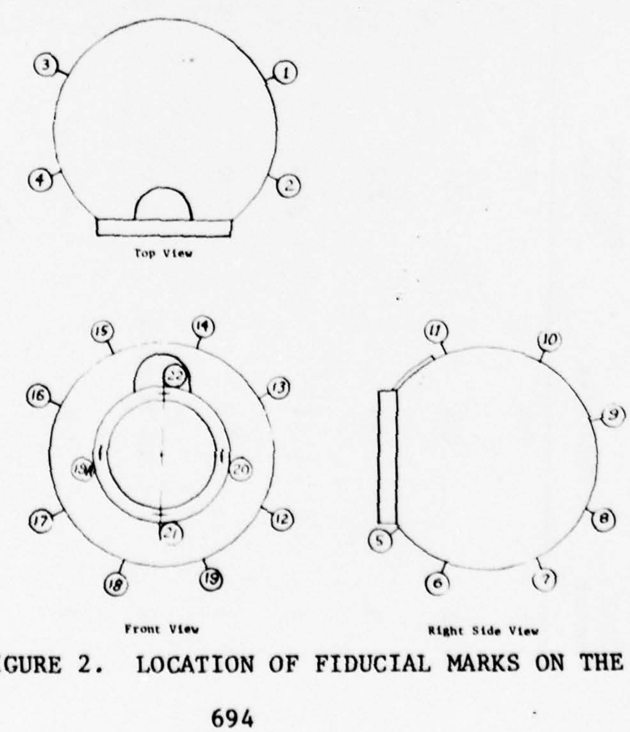


FIGURE 2. LOCATION OF FIDUCIAL MARKS ON THE VESSEL

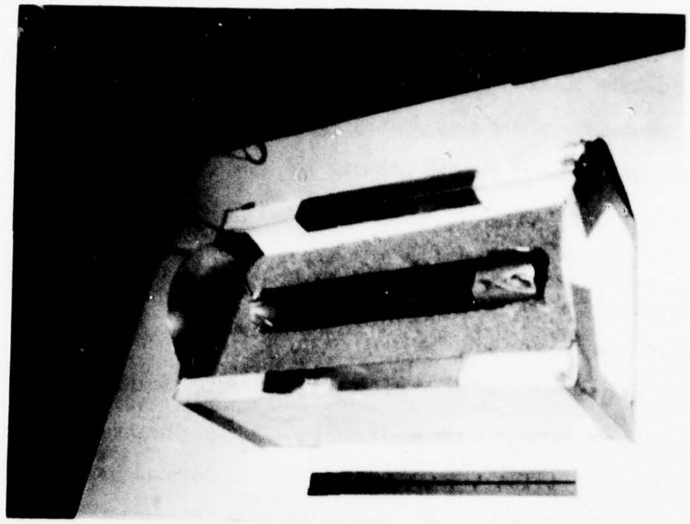
as will be seen here, the vessel distortions were, in some cases, far from spherical and the interpretation of individual readings as strain requires caution, as some measurements may be more a measure of distortion or shape change than of actual plastic stretching of the vessel skin. Measurements on the face of the reinforcing ring were made with similar precision.

Figure 3 shows an example of a pipe bomb surrounded by sand to serve as a fragment restraint. A stand-off air gap for the sand was not used in the vessel experiments reported here.

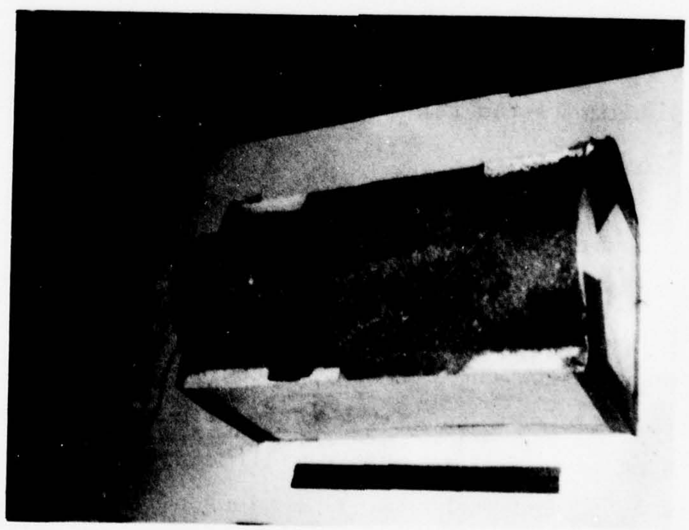
Table 2 shows the distortion distribution data obtained from the fiducial mark readings reported as strain. Also shown in Table 2 are the overall average strains from the vessel skin fiducial marks and two other partial averages to help assess the effect of the charge shape on the vessel response. The End Average is the average of the strains between fiducial mark pairs 1-2, 3-4, 12-13, and 16-17. Reference to Figure 2 shows that these gage lengths extend across the portions of the vessel opposite the ends of the cylindrical charge shapes. The Side Average is the average of strains between fiducial mark pairs 5-6, 7-8, 9-10, 10-11. These gage-lengths lie in a great circle opposite the sides of the cylindrical charges. The Side/End Ratio shown in Table 2 is simply the ratio of the Side Average to the End Average strains.

It will be noted that if the vessel response to spherical charges were spherically symmetric then the Side/End Ratio should equal unity. The response of the vessel does not show such spherical symmetry as the Side/End Ratio reveals for spherical Shots 1-4. However the Side/End Ratio departs much further from unity for the cylindrical charges as an indication of the charge-shape effect. In some cases the ratio is negative because the End Average strain is negative. This effect will be discussed later.

Figures 4, 5, and 6 show similar views of the vessel taken after Shot 6, the first pipe bomb shot, and after Shot 10. Of particular note in Figure 4a are the two localized bulges on either side of the weld along the top profile of the photo. More generalized strain in these areas largely obliterated the appearance of these bulges in later shots. They were probably caused by the impact of large fragments from the pipe bomb. No surface



a. View of Pipe Bomb in Partially Filled Fragment Restraint Container

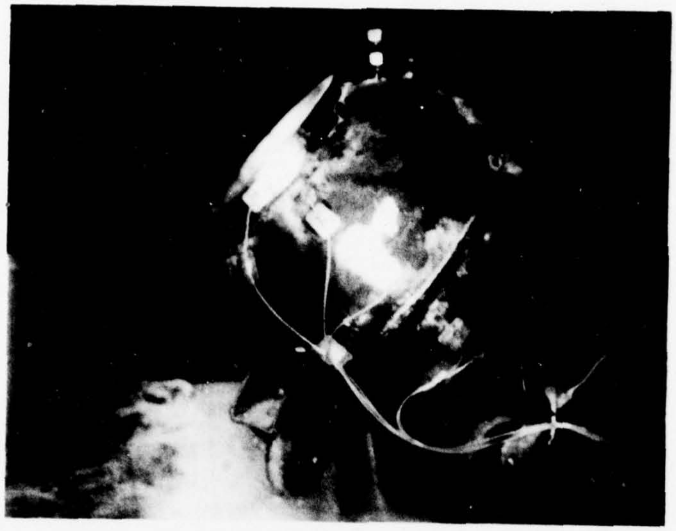


b. View With Full Fragment Restraint

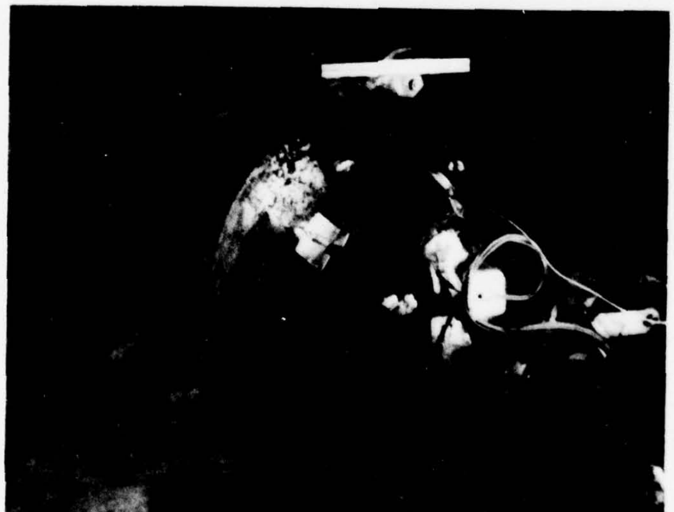
FIGURE 3. CHARGE LAYOUT FOR SHOT 10

TABLE 2. PLASTIC STRAIN DISTRIBUTIONS

Fiducial Mark Pair	Original Length, In.	Strain on Each Shot, percent										Total Change	
		No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	Mils	Percent
1-2	9.489	.03	.17	.44	.22	.08	-.01	.06	-.01	.17	.15	124	1.31
3-4	8.228	.02	.17	.51	.24	.15	-.05	.12	-.12	.00	.11	95	1.15
5-6	6.045	.13	.03	.50	.30	.30	1.39	.35	.13	3.22	1.57	479	7.92
6-7	9.389	-.06	.46	.41	.10	.54	1.49	.52	.10	1.88	.51	558	5.94
7-8	9.441	.37	1.05	1.24	.13	.84	2.02	.58	.34	2.49	1.80	1025	10.85
8-9	8.982	.00	.71	.99	.40	.66	1.67	.33	.17	2.52	.72	734	8.17
9-10	9.174	-.06	.49	1.10	.59	.57	1.85	.20	.09	2.94	.63	770	8.39
10-11	9.607	.00	.24	.55	.58	.36	2.04	.23	.15	1.36	1.50	674	7.02
12-13	8.910	-.06	.19	.30	.00	.22	-.10	.04	-.03	.25	.30	110	1.25
13-14	9.096	.01	.07	.40	.13	.23	-.23	.11	.01	-.21	.22	67	.74
14-15	9.913	.01	.17	.28	.08	-.03	-.78	.00	.14	-.01	.42	27	.29
15-16	9.058	-.03	.22	.76	.16	.16	.02	.11	.10	.24	.19	143	1.58
16-17	9.295	.01	.16	.64	.17	.32	-.25	.09	-.04	.01	.15	117	1.26
18-19	8.559	NR	.08	1.04	.00	-.02	-.44	-.09	-.09	-.27	.46	72	.84
19A-20	12.84	.03	.17	.04	.03	.09	-.12	-.14	-.28	-.52	1.01	-92	-.71
21-22	13.28	.02	.00	.00	.00	.04	.11	.29	.23	.86	.23	248	1.86
Overall Skin Average		.029	.301	0.655	.221	.312	.616	.189	.065	1.042	.624		4.05
End Average			.172	.472	.159	.194	-.102	.079	-.052	.107	.178		
Side Average			.497	.799	.349	.544	1.744	.368	.161	2.401	1.123		
Side/End Ratio			2.87	1.690	2.19	2.802	-17.10	4.66	-3.08	22.49	6.23		



a. After Shot #6



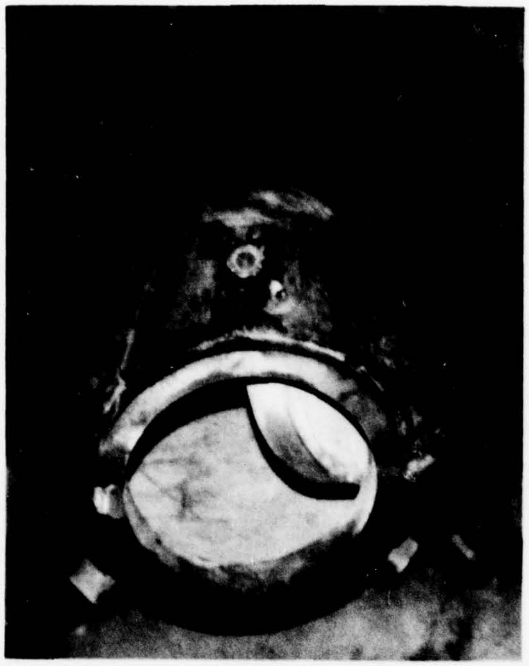
b. After Shot #10

FIGURE 4. SIDE VIEWS OF VESSEL

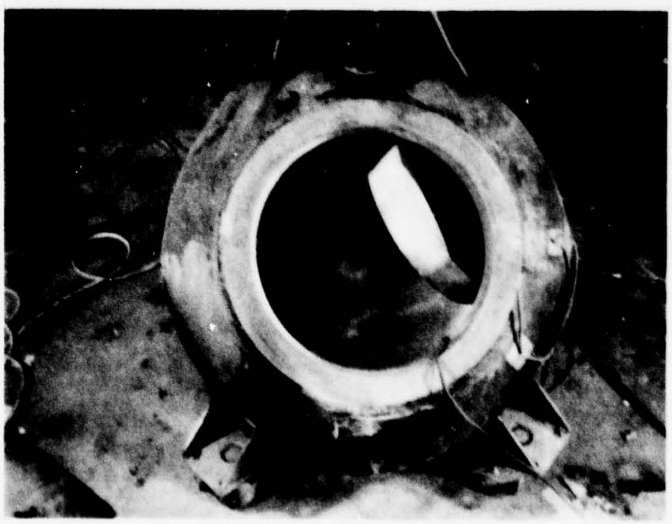
a. After Shot #6

b. After Shot #10

FIGURE 5. REAR VIEWS OF VESSEL



a. After Shot #6



b. After Shot #10

FIGURE 6. FRONT VIEWS OF VESSEL

disturbance by the fragment impact was caused on the inside however. In Figure 4b, the general swelling of the vessel along the vertical plane between the caster wheels is apparent. One caster wheel was lost during Shot 10. The nut securing the wheel in place was found to have stripped threads as the source of failure. Previously, on Shot 7, a segment of about 120 degrees was broken out of the tire on the same caster. The fracture occurred through the rubber portion only.

Comparison of the vessel appearance in Figures 5a and 5b, and 6a and 6b reveals the nonuniform nature of the strain produced by the cylindrical charges.

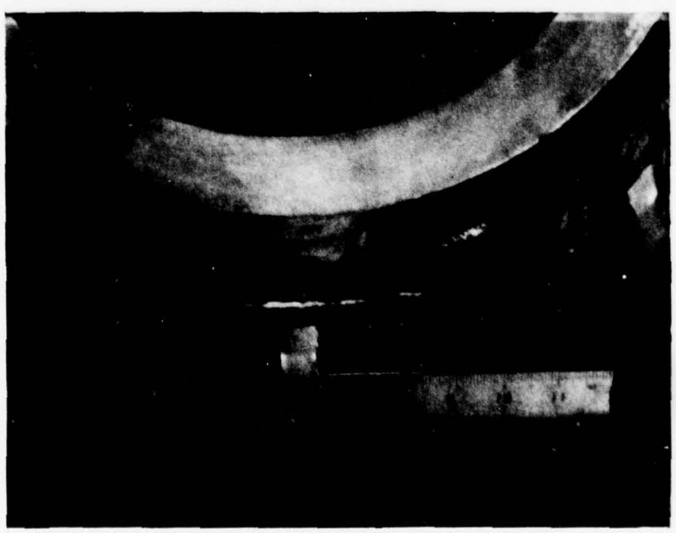
Figure 6b shows the location of the crack produced by Shot 10, located just below the port. Also shown in Figure 6 is the smooth nature of the interior of the vessel. As expected, the 2.5-in. sand layer provided complete protection against the formation of fragment craters in the vessel surface.

Figure 7 shows two views of the crack in the vessel produced by Shot 10. The crack did not open appreciably, as evidenced by the nearly 30 seconds venting time for the contained gases observed for Shot 10. The crack comes within about 1/16-in. of the weld metal on both the outside as shown and also on the inside of the vessel. The maximum displacement of the crack edges with respect to each other is approximately 3/16-in.

DISCUSSION

An elastic-plastic computer program[1-3,16] to predict the performance of spherical blast-containment vessels has been developed at Battelle as an aid to understanding the performance of spherical blast containment chambers. The program uses a bilinear elastic-plastic model with linear work hardening for the stress-strain behavior of the metal. Due to uncertainties in the effect of strain rate on the material properties, especially the yield strength, these parameters are currently treated as adjustable parameters to make the predicted results agree with experiments. This code has demonstrated good agreement with the average residual strains produced by large spherical C-4 charges in a series of vessels nominally identical to

a. Side View



b. Front View

FIGURE 7. VIEWS OF CRACK IN VESSEL AFTER SHOT #10

the one evaluated in this program.[1,2,5,6] To obtain agreement with experiment a yield strength of 80,000 psi was assumed. This value also appears to predict results in good agreement with the average strain of the vessel skin for the bare spherical C-4 shots in this program as shown in Figure 8. The error bars shown on the data points show the maximum and minimum strains recorded by individual fiducial gage lengths on each vessel. Although a strain-hardening effect is known[1,5] to exist for repeated shots, it is expected that the residual strain for the 1.56-lb Shot No. 1 was sufficiently small that no appreciable strain-hardening occurred as a result of this shot. However, the 2.56-lb Shot No. 2 produced sufficient strain that strain-hardening effects are expected to be present in subsequent shots which would tend to reduce the observed strains below those which would have occurred if a new vessel had been employed for each shot. At present there is insufficient data to assess the magnitude of the strain hardening effect with certainty.

Shot No. 5 provides some indication that the strain-hardening effect in the vessel was still quite small at that point in the test series. The average strain produced by Shot No. 5, a compact cylindrical charge with L/D = 0.89, was very close to that produced by Shot No. 2, a spherical charge of the same weight. In addition, the Side/End Ratios given in Table 2, show that this compact cylindrical shape is quite similar to a sphere in its effect on the vessel. One departure from this similarity was a small bulge produced opposite the charge-end away from the detonator.

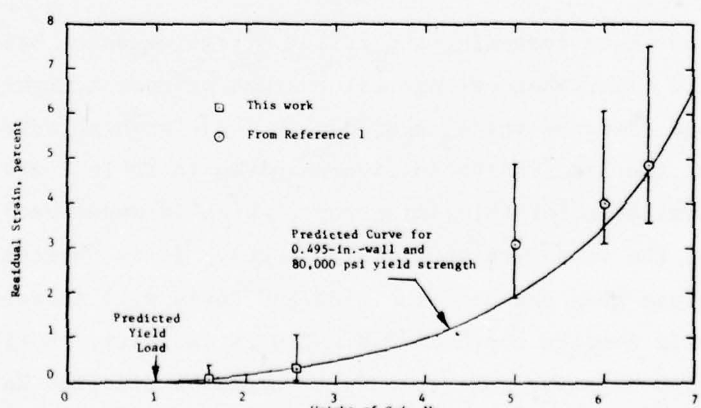


FIGURE 8. COMPARISON OF PREDICTED AND OBSERVED RESIDUAL STRAINS FROM SPHERICAL CHARGES

The 2.5-in. layer of sand around Shot No. 3 produced strains well in excess of that expected for a bare charge. If strain-hardening effects are ignored, the average strain produced was equivalent to a bare charge of $\sim$ 3.4 lbs. Inclusion of strain hardening has the effect of increasing the equivalent bare charge weight. It was not determined in this study how the effect of enhanced momentum transfer to the vessel wall by a surrounding sand barrier scales with total charge load and relative sand barrier thickness. This subject is treated more fully in References 12 and 13.

If the premise that little strain hardening had occurred in the vessel when Shot No. 4, the steel wool energy-absorber test shot, was fired, then it appears that the steel wool had a beneficial effect in reducing the strain produced by the 2.5-lb spherical C-4 charge. The average strain in the vessel produced by Shot No. 4 was $\sim$ 26.6 percent less than that produced in Shot No. 1. The specific explosive load in this experiment was $\sim$ 0.6 lb C-4 per ft^3 of containment volume. This is appreciably in excess of the specific loads of 0.080-0.15 lb C-4/ft^3 used by Gross, et al of Artec Assoc.[17] Quantitative comparison of the present results with those of Gross, et al is difficult due to the different response regimes of their vessel [primarily elastic[18]] and the present vessel [appreciable plastic deformation[2,16]]. However, qualitatively, it appears that the beneficial effects of the steel wool energy-absorber, as used in these experiments, is somewhat less than might have been expected based on their results. This is probably due to the higher specific explosive load and hence higher specific energy load tending to saturate the energy absorber and thus rendering it relatively less effective.

Significant data regarding the effect of charge shape has been obtained. It is quite clear that cylindrical charges produce a highly anisotropic shock wave field and that the vessel responds to this large anisotropy. Although qualitative, the Side/End Ratio figures given in Table 2 are at present the best measure available for this anisotropy, which is superposed on the non-uniform response of the vessel to spherical charges. It is obvious that as the End Strain Average gets smaller, the Side/End Ratio will increase, and that for a zero End Strain Average the Side/End Ratio is infinity. Further decreases in the End Average to negative values leads to negative Side/End Ratios, which should be interpreted as larger measures of distortion anisotropy.

Detailed comparisons of the anisotropic effects of the various charges fired in this program are at least partially confounded by the cumulative change in the vessel shape with the repeated firing of cylindrical charges. The results do appear to be in general agreement with the notion that greater L/D ratios lead to larger anisotropic effects, and that the presence of a steel and sand barrier on the outside of the cylindrical charges further enhances the anisotropic effect over that of bare charges. These findings are consistent with less dramatic charge-shape effects investigated previously(1,5), in which the influences of suit-case shapes and truncated cubes were observed.

SUMMARY

An effective lightweight system capable of preventing the production of fragment craters from pipe bombs on the interior of containment chambers was found. It consisted of an annulus of common sand $\sim$ 2-2.5 in. in thickness surrounding the pipe bomb, and in contact with it, or with an air gap up to 1-1/4 in. for 2-in.-diameter Schedule 40 pipe. This system was not optimized during this program and further studies have been conducted to determine the minimum sand layer requirements for various size pipe bombs.(12,13)

A 2-ft-diameter spherical steel explosion containment chamber was designed, fabricated, and extensively tested. The chamber was caster-wheel-mounted, has $\sim$ 0.5 in. wall thickness, and weighed $\sim$ 400 lbs.

For spherical charges, good agreement with computer program predictions of residual plastic strain was obtained for 1.5 and 2.5 lb charges. The predictions in agreement with experiment used an 80,000 psi yield strength model for the vessel material.

For long bare cylindrical charges, strong anisotropic effects were observed. The containment chamber strain opposite the sides of the charges was much larger than that opposite the charge ends.

For pipe bombs with the fragment restraint system, the anisotropic strain effects on the chamber were also large. In addition, it was found

that 1.5 lb explosive charges in pipe bombs with a sand restraint system for the fragments produced significantly greater plastic strains than equivalent bare charges. Neverthele. s the portable chamber demonstrated a significant containment capability for several repeated charges of this weight with no interior surface disturbances from fragment impact with the new fragment restraint system.

To date it would appear that this technology will be adopted in foreseeable explosion containment vessel prototypes.(15) It cannot be overemphasized that the successful use of elastic-plastic vessel responses to achieve portable, affordable, low-usage explosion containment chambers is highly related to the material fracture properties at the lowest intended service temperature.(11) The dramatic anisotropic effects of pipe bombs observed in this investigation strengthen our conviction on this point, although we are confident that solutions will continue to be found as the need for explosion containment technology expands.

ACKNOWLEDGMENTS

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EMERGENCY RESPONSE TRAINING

FOR

EXPLOSIVES TRANSPORTATION

PRESENTED BY

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WASHINGTON, D.C.

What do you think the heroic defenders of the Alamo, or anyone back around 1836 for that matter, would have had to say about some Washington dude coming to town to speak on emergency response for explosives transportation? Probably not much, and, whatever the comment, it no doubt would have been very descriptive and negative. Are community attitudes really much different today? Recently, they seem to be, at least to the point that the public is beginning to recognize the existence of hazardous materials (HM) in communities. Just how this awareness is reflected is extremely important for the economic health and security of our nation, as well as the public safety. Reaction can be from ignorance and fear, thus disruptive and totally unproductive. Or, it can be in the nature of informed understanding, support and cooperative planning.

Fortunately, explosives transportation has a relatively good safety record; but it is not perfect. Figures 1 and 2 show the latest statistics on accidents reported to the Materials Transportation Bureau via the Hazardous Materials Incident Reporting System. There have not been any catastrophic events during this period. By catastrophic, I mean numerous deaths, injuries and extensive property damage. However, we can recall catastrophic accidents for both commercial and military explosive shipments. 1973 and 1975 saw quite a few incidents and injuries.

Why is the record better than that for some other hazardous materials? Maybe it is due in part to special precautions and hazard recognition. Maybe we have been lucky. In any case,

we need to ask ouselves such questions as: Why accidents still did and do occur? What could have been done to prevent or reduce their seriousness? What is different now than it was the last time we reviewed our explosives transportation safety program? Do we have a comprehensive, systematic emergency response training program and plan? How do we, or how can we, integrate our knowledge and capabilities with communities adjacent to our installations and along the routes traveled by explosives items? I am referring not just with respect to explosives, but all HM. These are just a few questions to stimulate your thoughts.

I sincerely hope you will do some very serious thinking about this matter. There is always some accident waiting to happen. The impact depends upon how well we are prepared to eliminate or control the situation.

People do not automatically react correctly to emergencies unless they have learned to do so and are thoroughly prepared to assess the situation and make right decisions. How do we reach that readiness state? Thorough experience, training and simulated exercises certainly are basic requirements.

I would like to be able to say that everyone here will be fully qualified in explosives transportation emergency response upon the conclusion of my presentation. Obviously that is impossible. However, what I hope to accomplish is to provide some suggestions/guidelines as to how it can be done.

The ground work is layed and the frame is up, but we still have the finish work to do. My primary purpose in being here is to ask your help in completing the task.

Some, but probably not everyone here, are aware that the National Fire Protection Association (NFPA) has developed for the Department of Transportation (DOT) a self-standing, performance-oriented course for training emergency services and communities how to plan against and effectively control hazardous materials transportation accidents. We are talking about fire, medical, law enforcement, disaster control, EPA type, maintenance crews, city managers, shippers, carriers and the many others who could be involved in HM accidents.

This course package has been marketed and taught by NFPA since May of this year. It has been very favorably received because it is the first course ever offered which helps provide the answer to the frequently-asked question: *We are aware that hazardous materials can be dangerous and pose a threat, but what can we do about it?* The Secretary of Transportation has offered a complementary course package to each Governor, the Mayor of D. C. and several Federal agencies.

The course consists of eight units totalling about 20 hours of instruction, including 963 colored slides, eleven (11) tape cassettes, a student performance manual, course coordinator's guide and some handouts. There is a strong interaction between all elements -- audio-visuals, coordinator and students-- and there are individual and team exercises because both approaches will ultimately be required in the real incidents. The bottom-line purpose of this course is to have a viable HM transportation emergency response plan developed and operating in every community in the country.

This course is really just the core. It provides the basic guidelines for those responsible for developing, testing, implementing and updating the plan. There are going to be variations because no two-communities are exactly alike. Consider for a moment the marked contrast between highly sophisticated paid city fire departments with training officers and the rural volunteers who might hop off a tractor or drop a chain saw and head for the accident scene in their car or pickup. Can the latter take additional time from their jobs to train -- or, even if they could, where would they go? Another complicating factor is the variation among states/cities as to who is in charge of emergencies. The Colorado statutes say it is the sheriff. Somewhere else it could be the fire marshal or the civil disaster coordinator. Just to make certain there is no misunderstanding, the course is for all persons involved in HM emergencies, not just fire-fighters.

Where the nature of particular types of HM or the quantities are unusual, additional training emphases needs to be placed on those materials. EPA has developed a course to protect its pesticide inspectors, but it is not designed for community operation plans. We have under development two such specialized emergency response supplements to our basic course, namely one on pipelines the other on radioactive materials transport.

Now we come to the part where I am going to challenge the military services and explosives manufacturers to pick up the ball and run with it. I am recommending that the military and industry experts get together and develop an explosive supplement to the

DOT-NFPA emergency response training course. Most, if not all, of the necessary training information and materials are probably in hand. What is needed is for someone to collect, consolidate, update and convert them into a compatible format.

We certainly stand ready to help develop a distribution plan and perhaps can provide some helpful advice during the development by virtue of our experience. I am not in a position to commit funds to assist you, and frankly do not feel that DOT should have to in this case. But again, I want to reiterate our willingness to cooperate otherwise.

The DODESB seems to me to be the logical organization to oversee such a project, or at least to act in a catalytic or coordinating capacity. So that the Board and those who might become involved in such an undertaking will have a better idea as to desired course format and what has been done, I am presenting to the DODESB, on behalf of the Department of Transportation, this complementary course package. I sincerely hope that it will be the initiator and stimulus for this very worthwhile and urgently-needed project. We look forward to your response.

I appreciate the opportunity to be here and would be be very pleased to discuss the subject further and answer questions any time during the seminar. All you have to do is find me. Thank you for your attention.

FIGURE 1. -- EXPLOSIVES TRANSPORTATION
INCIDENTS BY CLASS -- 1971-1977 1/

Explosives Classification	1971 (2,255) 2/	1972 (4,344) 2/	1973 (6,014) 2/	1974 (6,413) 2/	1975 (10,750) 2/	1976 (11,898) 2/	1977 (15,954) 2/	1971-1977 (60,000) 2/
Class A	13	5	11	7	21	5	6	68
Class B	5	2	4	3	4	7	4	29
Class C	8	7	6	12	6	4	6	49

1/ Incidents reported to DOT/MTB in compliance with Section 171.16, Title 49 Code of Federal Regulations.

2/ Parenthetical values are total incident reports received.

FIGURE 2. -- DEATHS, INJURIES AND PROPERTY DAMAGE FROM EXPLOSIVES TRANSPORTATION INCIDENTS -- 1971-1977 1/

	1971	1972	1973	1974	1975	1976	1977	1971-1977
Deaths:								
Explosives	2	0	0	0	0	0	0	2
Total	23	12	21	32	27	18	31	164
Injuries:								
Explosives	1	0	52	0	28	1	0	82
Total	253	294	474	900	655	820	750	4190
Property Damage:								
Explosives	$330,415	$50,001	$1,252,035	$243,000	$321,000	$0	$95,000	$2,241,450
Total 2/								

1/ Incidents reported to DOT in compliance with Section 171.1.6, Title 49 Code of Federal Regulations.

2/ Not available.

Safe Transport of Munitions

(STROM)

Presented by:

Burton M. Rudy
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Military Traffic Management Command
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SAFE TRANSPORT OF MUNITIONS

The Safe Transport of Munitions (STROM) is not a new topic, but its importance has magnified tremendously in recent years due to the introduction of more sophisticated weapons with more powerful explosives, as well as population increases near shipping routes.

A review of explosives incidents that occurred in Roseville, California (Figure 1) and Benson, Arizona (Figure 2) will help to understand some of the problems involved.

A Southern Pacific train arrived in the Roseville rail yard at approximately 6:00 a.m., on the 28th of April, 1973. Included in the train were railcars loaded with high explosive bombs destined for Vietnam. Two hours later, at approximately 8:00 a.m., an explosion occurred in one of the bomb laden cars. By propagation, 18 of the cars were destroyed by explosions over a period of 2-1/2 hours.

Bombs strewn throughout the remaining burning debris continued to explode until 4:00 p.m. the following day.

There are many hypotheses as to the cause of the incident, but a complete report is not yet available due to ongoing litigation involving the Southern Pacific Railroad and the United States Government.

A little less than a month later, on May 24 at approximately 7:00 p.m., another Southern Pacific train, this one with 12 cars loaded again with high explosive bombs destined for Vietnam, was approaching Benson, when it was racked by a series of explosions which continued for 6-1/2 hours, destroying all 12 bomb laden cars. Fortunately, the train was 5 miles from the nearest home.

The National Transportation Safety Board, in its Benson report, hypothesized that the initial explosion was caused by a fire which most likely originated when sparks were thrown from the car brake shoes and ignited the floor boards, which were impregnated with sodium nitrate from a previous lading.

Although property damage was quite extensive, totaling well over $3,000,000, the Roseville and Benson incidents fortunately caused few personal injuries and no fatalities.

However, a recent explosives incident occurred in Iri, South Korea (Figure 3) where nearly 60 people were killed and hundreds injured by the explosion of one carload of dynamite. We can imagine what would have

happened had the Roseville and Benson incidents occurred as the trains were passing through heavily populated urban areas. This potential for disaster has long been recognized and a special note of it was made by the National Transportation Safety Board in its Benson report. One point must be stressed — it is this potential for disaster that is the greatest concern to all involved in the STROM program.

The Benson incident, occurring so soon after Roseville, brought an old problem to the surface: How to prevent, or limit the effects of explosives incidents in railcars, and mass detonation of containerized munitions in port areas and aboard ships.

Our task is to learn everything we can about the problem and determine what corrective actions can be taken.

The Department of Defense started to attack the problem soon after the Benson incident, and developed the STROM Study Plan. The plan stemmed from recommendations made by its Explosives Safety Board in the fall of 1974. The Safety Board recommended that technical and operational feasibility studies be conducted in six areas:

1. Limited use of spacer cars.

2. Heat sensors with alarm systems.

3. Utilization of fire experience and test data previously acquired by the Naval Weapons Center, China Lake, California.

4. Use of installed fire protection systems.

5. Use of buffer systems other than spacer cars.

6. The use of all steel cars.

The Safety Board also recommended that a Project Manager be named by the Military Traffic Management Command (MTMC), with the Safety Board and other Department of Defense components to be on call as required. MTMC prepared the study plan, which outlined the various actions comprising the STROM program, with the command serving as Program Coordinator.

The study plan is flexible, so that other areas can be considered as the program progresses. Two additional areas of study, besides the six previously recommended, have already been incorporated into the plan. The first encompasses railcar stability, as well as shock and vibration control. The second is concerned with containerized munitions.

The study does have one specific constraint. In order to confine the scope of the study to an acceptable limit, only Class A, or detonating type explosives are being considered.

Our study objective is: To determine procedures and methods which are technically and operationally feasible and economically acceptable that will prevent, or limit the effects of explosives incidents in railcars, and mass detonation of containerized munitions in port areas and aboard ships.

In order to meet this objective, certain tasks were assigned to study participants according to the availability of special expertise and physical assets. The four primary Department of Defense participants are: The Army Ballistic Research Laboratory, Aberdeen Proving Ground; the Army Ammunition Center, Savanna, Illinois; the Naval Weapons Center, China Lake, California; and MTMC including Headquarters and the Transportation Engineering Agency. Other organizations, both within and outside the Government, will be approached for information and consultation as required. Points of contact have already been officially set up at the Department of Transportation and the Association of American Railroads.

There are 13 tasks to be completed by the participants. So as to logically develop all aspects of our objective, the tasks have been categorized into six areas as follows:

I. Background.

1. Identify the regulations which govern the shipment of munitions by rail, and estimate carrier compliance.

2. Identify the hazard characteristics of DOD munitions during transportation.

3. Determine, on a statistical basis, accident cause and scope of damage to personnel and property, in reference to munitions transported by rail.

II. Traffic Pattern.

4. Analyze the distribution of munitions, and determine whether cargo flow patterns minimize intransit exposure, in regards to population density.

III. Equipment Considerations.

5. Study the consequences of restricting future munition shipments to railcars of all steel, or otherwise non-combustible construction.

6. Determine if railcar stability, as well as shock and vibration control, can aid in the prevention of explosives incidents in the rail movement of munitions.

IV. Fire Protection Systems.

7. Determine if sensors in a munitions carrying car, coupled to an appropriate alarm system, will provide adequate detection of dangerous heat buildup in the car.

8. Study the use of fire protection systems, within or on railcars transporting munitions, with the objective of preventing or controlling fires.

9. Examine the application of test data and fire experience acquired by the Naval Weapons Center, to the reduction of the risk of fire in railroad rolling stock.

V. Buffer Systems.

10. Investigate the use of buffer systems, other than spacer cars, to reduce the risk of explosives propagation from car to car.

11. Study the use of spacer cars to prevent the propagation of an explosion between railcars.

12. Study the use of containers on flat cars and trailers on flat cars for transporting munitions, as a means to prevent or minimize explosives incidents.

VI. Port Areas/Ships.

13. Analyze methods for preventing, or limiting the effects of, mass detonation of containerized munitions in port areas and aboard ships.

Each of the tasks, as well as subtasks, has a time schedule and all are projected to be completed within a 27-month time frame. The plan calls for a report, with recommendations, to be submitted for each task. These reports are to be analyzed by MTMC, which will then develop and publish a final report.

The total cost of the program is quite substantial, almost $3 million. Both the Army and the Navy have allocated funds in support of the STROM effort.

The program is fully active. The first coordination meeting was held at MTMC HQ in Washington, DC on 16 November 1977, and the first working meeting on 29 March 1978 at MTMCTEA in Newport News, VA. Program plans have been finalized and a number of tasks started January 1978. Twelve of the 13 tasks are scheduled to start sometime prior to October 1978.

Quarterly progress reports are being submitted, and general review meetings held semi-annually with the first held at the Ammunition Center 21-22 June 1978. The final report is scheduled to be published September 1980, six months after all tasks are completed.

Although none of the tasks have been completed as yet, reports received from the performing elements have included the following findings and recommendations, most of which are tentative and subject to further study:

1. Types of railcars used to transport munitions have been identified, along with special equipment requirements, such as spark shields, roller bearings and composition brake shoes.

2. It has been determined that 26 ammunition items will comprise 80% of the dollar value of projected procurement of DOD munitions. These 26 items will form the basis of a matrix being constructed by study participants, which will list hazard/sensitivity characteristics of selected DOD munitions.

3. A rail network model is being constructed by MTMC which will give population densities along routes used for transporting class A explosives. From this model we will identify routes which will minimize intransit exposure.

4. Preliminary findings have revealed that in order to reduce the possibility of munition train derailments, munition carrying railcars should be the shortest practical length, have the longest practical couplers, and be loaded as near to capacity as possible.

5. Potential heat sources which can cause railcar fires have been identified. These include yard fires, and overheated journal boxes and brake shoes.

6. A review of the state of the art of buffers has been completed and further study of buffering systems will include: suppressive shielding, stowage configurations, packaging and packing, rod or tube barriers for individual rounds and fire retardants.

7. Preliminary findings on the use of spacer cars concluded that derailments of munitions trains occurred more frequently than normal, when using this method.

Figure 1 - Roseville, California


Figure 2 - Benson, Arizona

A woman cries and a man buries his head in sorrow over the damage. (AP)

A man stands near the crater made by the bomb. (AP)

14,000 Koreans Homeless After Blast

SEOUL, South Korea (AP) – Thousands of homeless families huddled in makeshift tents in near freezing temperatures Saturday after the worst peacetime explosion in South Korean history. Police suspected arson as the cause of the dynamite blast in the southwestern city of Iri.

At least [illegible] persons were killed, nine were missing and 1,340 injured, many of them critically, when 30 tons of dynamite blew up Friday night aboard a freight train parked at the railroad station.

Officials feared the death toll might go higher as more rubble was cleared away. President Park Chung-hee personally inspected the city and ordered an immediate investigation into the cause of the blast.

Police sources said Shin Moon-il, 37, ... investigators he spotted a small fire inside the car just minutes before the explosion.

The guard attempted to extinguish the flames, but found it was out of control and ran away shouting "Fire!" sources said.

The sources said police were looking into the possibility of arson.

About 9,500 homes and buildings were destroyed and about 14,000 persons left homeless by the explosion.

The car-shattering blast was heard within a 10-mile radius.

Damages were estimated at $10 million and President Park ordered the same amount in immediate relief measures for the leveled city.

... thousands of army troops, civil defense corpsmen and students were mobilized to remove the debris.

Families picked through the rubble and gathered whatever was left of their personal belongings. When darkness fell, they returned to the tents which provided little protection against the wintry weather.

At the railroad yard, tracks were blown off or twisted. A nearby theater caught fire and its tin-plate roof caved in, trapping 700 persons. At least six bodies were found.

The explosives were being transported by Korea Explosives Co. in Seoul to the provincial capital of Kwangju, south of Iri, for sale to a mining and

Figure 3 - Iri, South Korea

Blast waves produced by a pyrotechnic flash-mixture compared to those produced by high explosives

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1. Introduction

In test series, conducted in order to gain a deeper insight especially in view of accident prevention, into the destroying effect of pyrotechnic-mixtures, 5 kg of a flash-mixture consisting of 30 % Al and 70 % $KClO_4$ were fired within a medium sized family house (constructed of bricks).

The result of this experiment was a complete destruction of the house. Figure 1 shows the house before, figure 2 during and figure 3 after the experiment.

Because of this result systematic tests were conducted in order to get a more detailled knowledge of the effect of this mixture. Another aim was to compare the effects to those produced by high explosives.

In first experiments the overpressure of the blastwave which is produced by such a mixture was measured. This paper now, deals with these measurements.

2. Test material and test procedure

As substance for the tests a pyrotechnic flash-mixture consisting of 30 % Al and 70 % $KClO_4$ with following specifications was used:

Al:	specific surface area	5.86 m^2/g
	grain size	$< 70\ \mu m$

The oxygen balance of this flash-mixture is + 5.6 %.

For the measurements the substance was filled into small cardboard boxes. The experiments were conducted with masses of 50,

100, 200 and 500 g of the substance. The pressure was determined in distances from 1 to 5 m.

3. Experimental set up

The boxes with the substance were fastened to a gallow in free air, in such a way, that the disturbance of the measurements by ground reflecting shockwaves would largely be avoided.

The pressure time history of the blastwave was measured by a piezoquarz, which was mounted in the hollow of the tip of a speartype housing. With this set up the side on pressure could be determined (1). In figure 4 a sketch of this set up can be seen.

4. Results

A typical record of the pressure time history of the blastwave is shown on figure 5. The reduction of this signal was in these first experiments, limited to the determination of the peakpressure p_s. In order to get this peak-pressure the signal was approximated by the function $p = p_s\, e^{-t\, c}$. By extrapolation to $t = 0$, p_s is obtained. This procedure is described for example in Ref. 2.

The results are listed in table 1.

Just for orientation it should be mentioned, that the duration of the positive phase lies between 700 µs and 1000 µs, and that the positive impulse lies between 0.1 and 0.2 barms.

5. Discussion of the results

The data of the overpressure were compared to those produced by the high explosive TNT and the TNT-equivalencies were computed. The data for TNT were taken from Ref. 2. The results are listed in table 1 and plotted in diagramm 1. It can be seen, that at small distances the TNT-equivalency is less than 1, whereas at greater distances the TNT-equivalencies increase and except for the 500 g-charge become greater than 1. In other words, near the charge the overpressure is less than that produced by the same amount of TNT, but it decreases more slowly and therefore exceeds that of TNT at greater distances. The charges with 100 and 200 g prove to be the most optimal blast producers.

Furthermore it was tried to describe the propagation of the blast wave theoretically.

For this description the theory of Brinkley and Kirkwood (3) was used. In this theory the dependence of the overpressure of the blast wave on distance is expressed by the following two differential equations:

$$\frac{dZ}{dR} = -F_1 \left[F_2(Z)\frac{2}{R} + P_0 \nu(Z) \frac{4\pi R^2}{E(R)} \right] \quad 5.1.$$

$$\frac{dE}{dR} = -\frac{4\pi R^2}{\gamma - 1} P_0 F_3(Z) \quad 5.2.$$

$$F_1(Z) = \frac{2Z^2(\gamma+1)/\gamma}{16\gamma^2 + 4Z\gamma(5\gamma+1) + Z^2(\gamma+1)(5\gamma-1)}$$

$$F_2(Z) = \frac{\gamma}{(\gamma+1)Z^3}\left(4\gamma^2 + 2\gamma(3\gamma-1)Z + (2\gamma^2-\gamma+1)Z^2\right)$$

$$F_3(Z) = (1+2)^{1/\gamma} \frac{2\gamma + (\gamma-1)Z}{2\gamma + (\gamma+1)Z} - 1$$

$$\nu(Z) = 1 - \frac{1}{3}e^{-Z}$$

P_o = ambient pressure

$Z = \frac{p_s}{p_o}$

E = energy of the blast wave

R = distance

γ = 1.4

The initial values, which are needed for the integration of this system are taken to be the measured values.

The initial value for Z could be taken directly from the measurements. The values for the energy of the blast wave were determined according to a procedure proposed by Brinkley and Kirkwood. From the plot of the overpressure versus distance the initial slope was determined, with the aid of equation 5.1 a first estimation of E_o could be obtained. Variing E_o until the solution of the differential equations was fitted to the measurements, the thus found last E_o was considered to be the correct value. The results of this procedure are shown in the diagramms 2 - 5. It can be seen that the theoretical curves fit the measurements very well, that's to say the propagation of the blast wave can be described by the theory of Brinkley and Kirkwood.

In diagramm 1 the TNT equivalencies for the distances where no measurements have been made, are computed on the basis of these theoretical results.

By integration of 5.1 and 5.2 towards the origin of the blast source, values for the energy coupled into the blast wave by the pyrotechnic mixture could be obtained at least qualitatively. They are as follows:

50 g	$\approx$ 4.0	10^4 Joule
100 g	$\approx$ 1.25	10^5 Joule
200 g	$\approx$ 2.5	10^5 Joule
500 g	2.9	10^5 Joule

The specific energy of this pyrotechnic flash-mixture is 8.5 10^3 J/g. Following percentages of this energy therefore can be found in the blast wave:

50 g	10 %
100 g	15 %.
200 g	15 %
500 g	7 %

From this values it can be seen that the masses 100 g and 200 g produce an optimal blast wave.

This result can also be recognized when plotting the overpressure against the scaled distance ($m^{-1/3}r$). This is done in diagramm 6

and it can be seen that the data for 50 g and 500 g are too low compared to the data of the other masses.

Now from the percentages of the energy coupled into the blast wave the reacting masses can be calculated. It was assumed that in the case of 100 g and 200 g all the material reacted, with this assumption it can be calculated that instead of 50 g only 34 g reacted and instead of 500 g only 233 g came to reaction. Now when computing with this "effective masses" the scaled distances again, and plotting the overpressure versus this distances diagramm 7 is obtained. The measured values now lie on a monotonically decreasing function.

Summary

The peak overpressure of the blast waves produced by a pyrotechnic flash-mixture (70 % $KClO_4$, 30 % Al) was measured. From these measurements the TNT equivalencies of this substance were computed. It could be shown that in the near field of the reacting charge the pressures of the blast waves were smaller than those produced by the same amount of TNT, whereas at greater distances the overpressures exceeded those of TNT. This behaviour is due to a slower decrease of the pressure of the blast waves produced by the mixture. Further more it could be shown, that the propagation of this blast waves can theoretically be described by the theory of Brinkley and Kirkwood. As a result of this description, it became evident that the reaction of this mixture depends on the mass. Charges with 100 and 200 g proved to be optimal blast producer, whereas the blast waves produced by 50 and 500 g were relatively weaker than those produced by 100 and 200 g. Further investigations will be undertaken to determine the cause for this behavior and the variation of the blast wave data from those of TNT results.

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Figure 1: Test house before the experiment

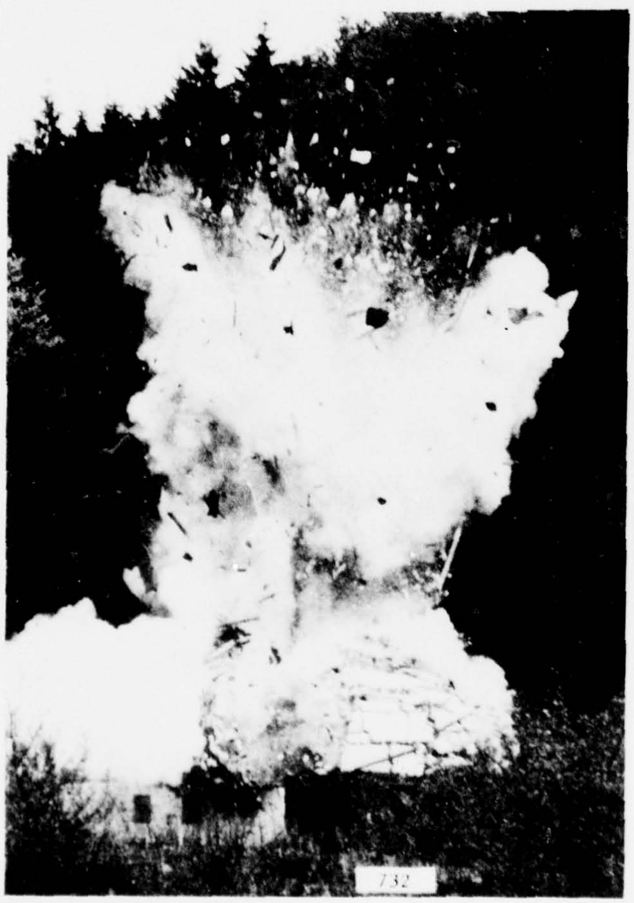

Figure 2:
Test house during
the experiment

Figure 3: Test house after the experiment

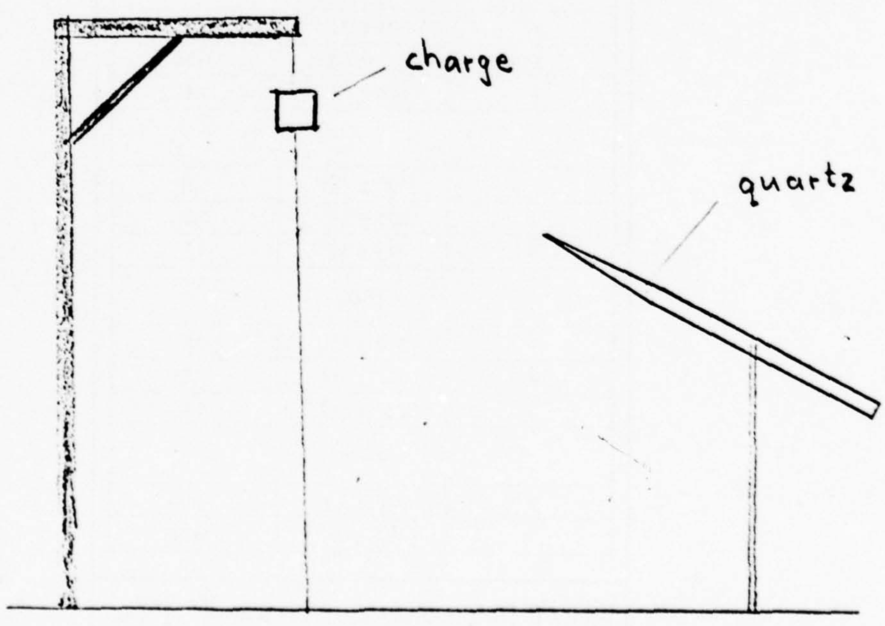

Figure 4: Sketch of the experimental set up

Figure 5: Pressure time history

Distance [m]	Pressure [mbar]	TNT Equivalency
	50g	
1	604 ± 72	0,6
1,5	363 ± 33	0,84
2	264 ± 8	1,1
	100g	
1	1126 ± 79	0,76
2	421 ± 12	1,3
3	213 ± 15	1,3
	200g	
1	1880 ± 180	0,8
2	552 ± 11	1,05
3	287 ± 17	1,1
	500g	
3	328 ± 23	0,55
5	185 ± 15	0,92

BICT	Table: Distance – Pressure	Wild 78 23 36

Table 1

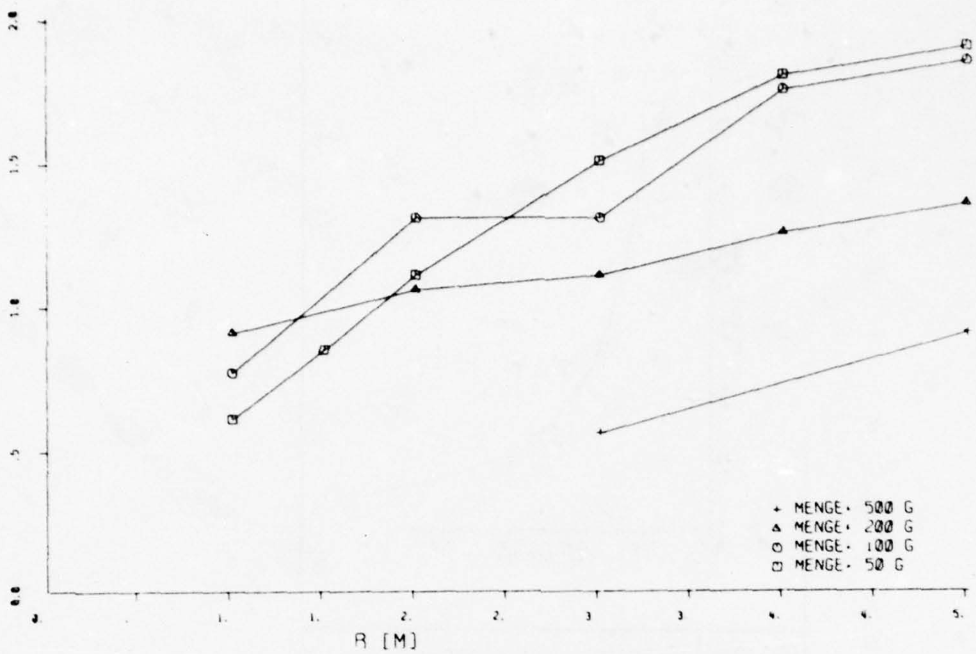

Diagramm 1: TNT-Equivalency

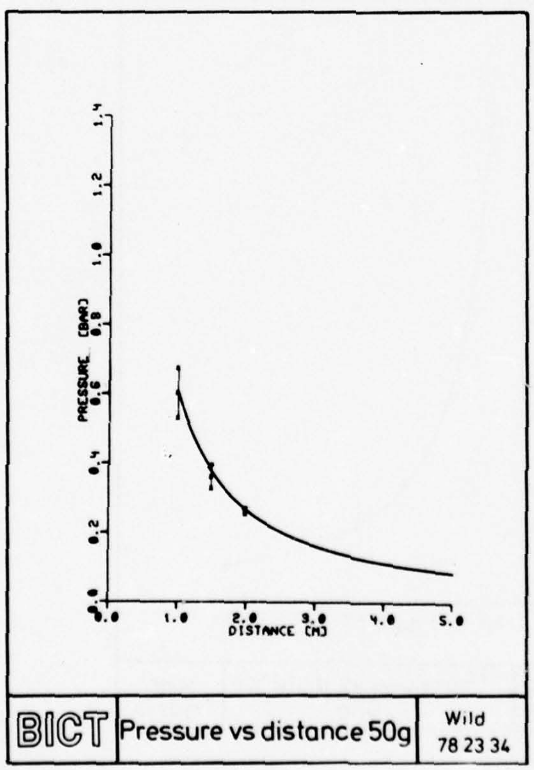

Diagramm 2

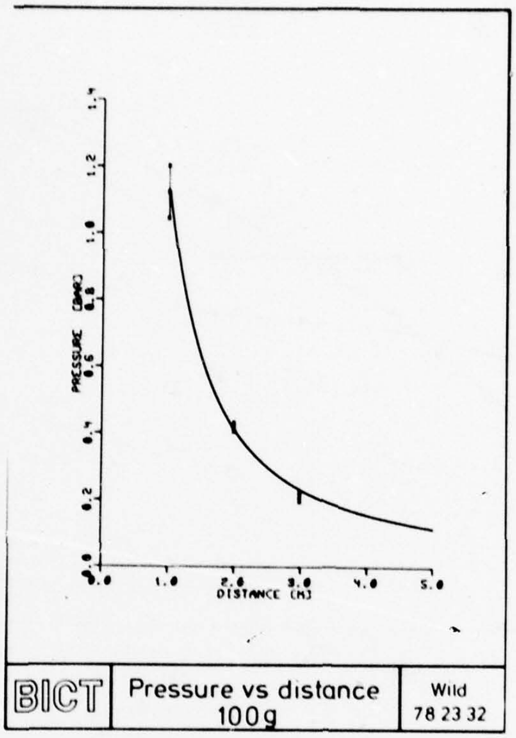

Diagramm 3

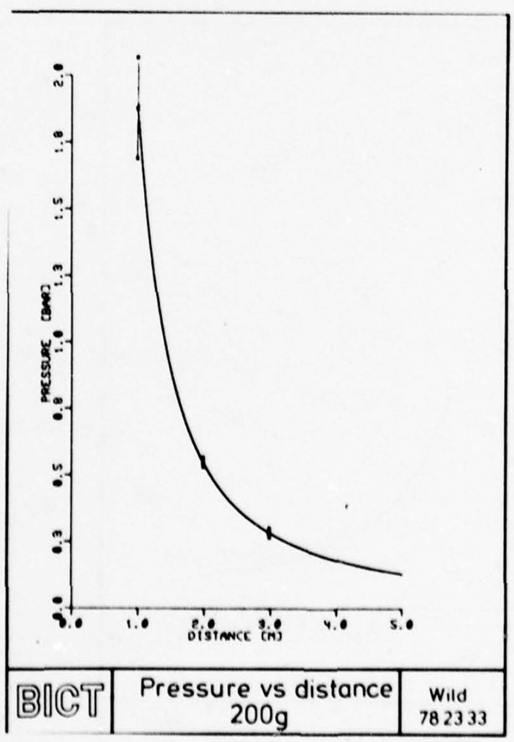

Diagramm 4

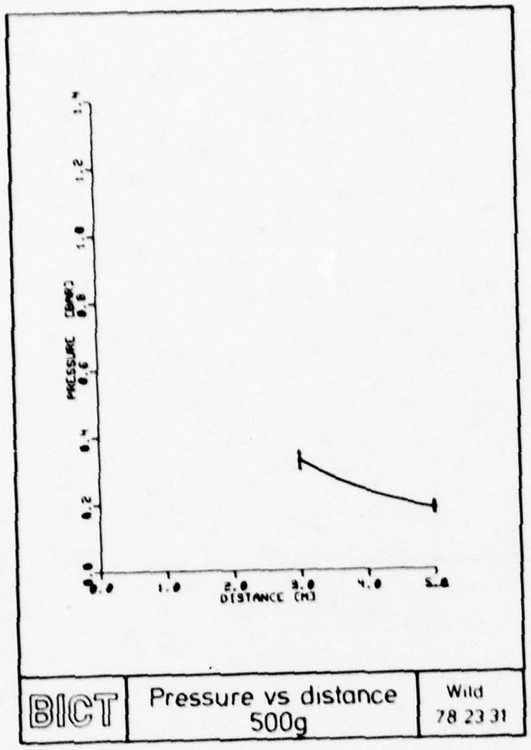

Diagramm 5

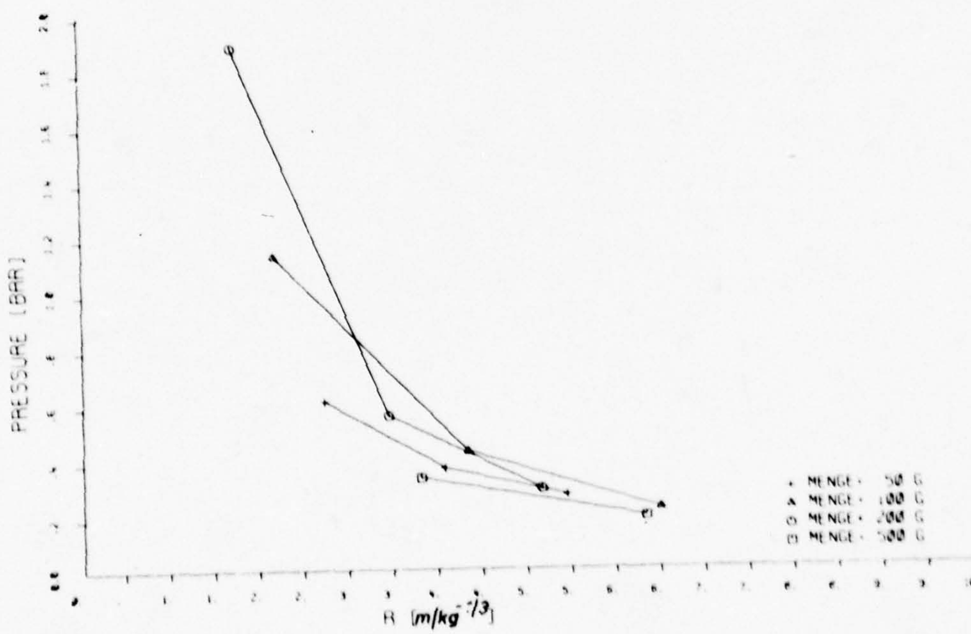

Diagramm 6

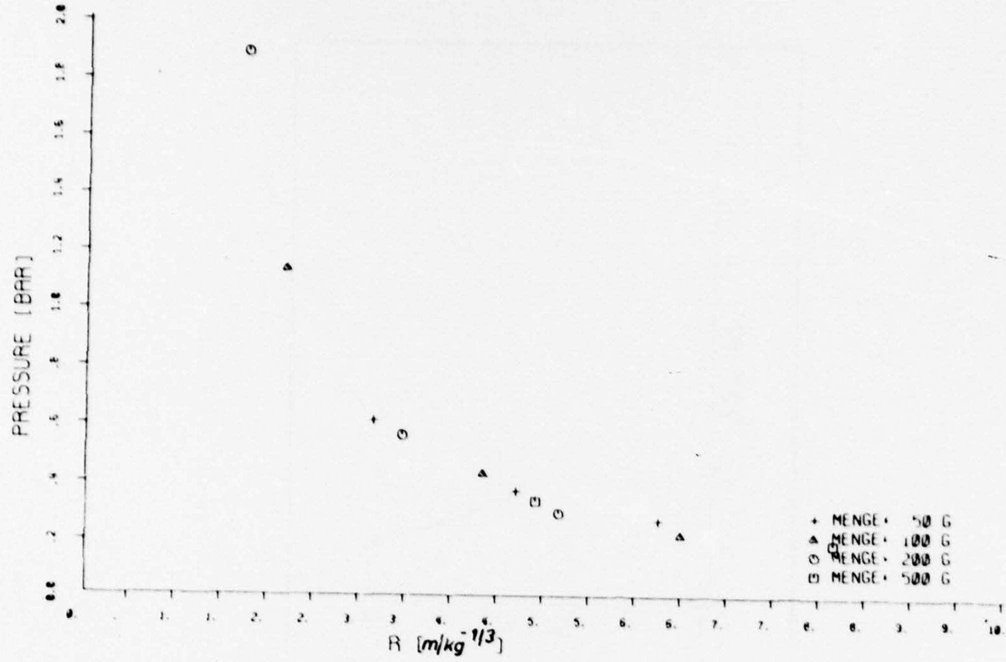
PRESSURE [BAR]
R [m/kg$^{-1/3}$]
+ MENGE: 50 G
▲ MENGE: 100 G
○ MENGE: 200 G
□ MENGE: 500 G

Diagramm 7

EIGHTEENTH DOD EXPLOSIVES SAFETY SEMINAR

RANGE CLEARANCE: A JOINT SERVICE PROBLEM

Part I: Relevant Issues

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Part II: Technology

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SEPTEMBER, 1978

ABSTRACT

Range Clearance: A Joint Service Problem

Range Clearance has recently been given increased visibility. This has arisen primarily because of pressure (1) to return old range areas to the private sector and (2) to make additional real estate available within the services for training purposes. Activity related to range clearance within each service is summarized and the critical aspects of planning a range clearance operation are detailed.

Lessons learned from limited operational experience at Frankford Arsenal, Kahoolawe Island, Culebra Island, and Putnam Target Range are discussed. The overall need to establish clearance standards is stressed and target standards are proposed.

The technology required to support range clearance is reviewed and both active and proposed equipment projects in support of the joint services are presented. Recommendations for a specialized equipment resources and manpower support are made. In conclusion, the need to establish legal certification criteria is addressed.

CONTENTS

PART I: RELEVANT ISSUES

I. INTRODUCTION AND PROBLEM SCOPE

A. General

Range clearance is a many faceted problem relating to the removal of munitions from training areas, combat areas, disposal areas in Continental United States (CONUS), overseas land areas and the ocean areas of the world area. The reasons necessitating clearance are:

(1) Return of former battle areas to normal civilian use, e.g., the Trust Territories and Civil War combat zones.

(2) Return of surplus military training and development areas to the non-defense sector.

(3) Clean-up of training/development areas to permit continuance of training exercises and development testing.

(4) Revised land use criteria permitting former disposal areas to be made available for urban development, highway construction, or resource extraction.

The Military Departments have been under increasing pressure in recent years to return real estate to the public domain in those areas adjacent to major urban areas, recreational areas of those areas, which are believed to have unique economic potential relative to mining industry or commerce, e.g., gas/oil resources, deep ocean terminals. Land use management within the services has required inventorying of land and sea ranges required to support development and training. Additionally, it is necessary to identify those areas redundant to current needs which require clearance before disposal. It is pertinent to separately review the official posture of the several Military Departments on land usage management and clearance philosophies being followed.

B. Department of the Army (DA)

The DA has been assigned lead service for the completion and refinement of applicable technology and development of new technology as it relates to all contamination including chemical, biological and radiological. The memorandum directing this action required that the Department of the Navy provide support in matters relative to explosive ordnance disposal. The Army has assigned responsibility to the Project Manager for Demilitarization of Chemical Munitions and Installation Restoration, Aberdeen Proving Ground, Maryland. Primary emphasis of this organization has been in the area pollution abatement. Initiatives under this joint assignment include ordnance clearance of the former Frankford Arsenal and old "O" Field at Edgewood Arsenal.

The Office of the Chief of Engineers completed a milestone study in 1975 of the problems associated with range clearance and "permitted" land use. This study was concerned with a few selected major installations and highlighted some of the technological problems.

More recently, a study was conducted by the U.S. Army Training & Doctrine Command (TRADOC) in 1977 on land requirements to support unit training. DA tactical training requirements have dictated that increasingly larger range and impact areas must be associated with expanded maneuver areas particularly if air support and air defense components are to be exercised. Since acquisition of additional land is not financially attractive, these requirements may call for clearance of former impact areas of contaminating munitions to provide training areas that meet current standards.

The following is a summary of DA target range areas:

Location	Acres (Approx.)	Status
CONUS	2.8 million	Active
Overseas	10,000	Active
Surplus	20,000	1,200 acres cleared

(Appendix A contains a more detailed breakdown).

C. Department of the Navy

A study was conducted by the Naval Sea Systems Command in 1972 and updated in 1976. This study highlights the magnitude and complexity of the clearance problem. It is to be noted that approximately 500,000 acres of ocean and coastal waters are contaminated through dumping, target practice, or offensive mine warfare operations.

The range complexes supporting both the U. S. Navy and the U. S. Marine Corps forces encompass both land and water areas dispersed throughout the continental United States, its possessions and territorial waters. Base rights agreements with foreign governments authorized the establishment of ranges in the Philippines, Japan, Okinawa, United Kingdom, Spain, and Italy. These ranges have been subjected to varying degrees of contamination which includes practically every type of explosive munition in the military inventory, experimental and test items, and even foreign ordnance. Additionally, there are still many areas under Navy control which were in the theater of operations during WWII. For example, there is extensive land and water contamination existing in the Trust Territory of the Pacific, despite annual clearance operations by the Pacific Fleet Explosive Ordnance Disposal (EOD) personnel.

Target area clearance is usually conducted on a nonscheduled basis and is normally limited to surface sweeps only. As a result, residual contamination levels are increasing in all of the active ranges

for which Navy is responsible. This increase is commensurate with usage; however, there are no provisions for recording range utilization data in a manner which will support contamination estimates. Because of the lack of records, assessment of the subsurface and underwater contamination is impossible unless extensive surface, subsurface and underwater surveys are conducted in each area. Current search equipment and techniques are not adequate to support a survey operation of this magnitude. Cost and feasibility notwithstanding, the unexploded ordnance (UXO) presents a serious hazard to people who inadvertently (or purposely) disturb a live item. The use of these areas, for any purpose other than range complexes, is severely restricted until the UXO hazard can be eliminated.

A summary of Department of the Navy target ranges follows:

Location	Acres (Approx.)	Status
CONUS	2.3 million	Active
Atlantic Area	15,000	Active
Pacific Area	8,000	Active
Returned to private sector	38,000	-

(Appendix A contains a more detailed breakdown). Of the approximately 2.3 million acres listed, about 600,000 are under the cognizance of the U. S. Marine Corps.

D. Department of the Air Force

The Department of the Air Force maintains an inventory of existing ranges within the Office of the Chief of Administration and Services (HQ USAF/PRE-R).

At the present time, three ranges that are excess to requirements have either been cleared, designated unclearable or are to be cleared.

The Department of the Air Force has identified one area of one excess range as unclearable based on the premise that "where the cost of clearance exceeds the real estate value, clearance is uneconomical, and not within the best interests of the Government."

A summary of Air Force target areas follows:

Location	Acres (Approx.)	Status
CONUS	7.0 million	Active
	55,000	Excess
Overseas	6,000	Active

(Appendix A contains a more detailed breakdown).

E. Requirement Areas

The challenge or problem presented by the need to clear ranges manifests itself in the definition of three distinct areas requiring additional effort. These include the need for

(a) a definition of planning parameters and the development of a planning model

(b) a coordinated definition of clearance criteria, and

(c) a dedicated equipment and equipment development support program.

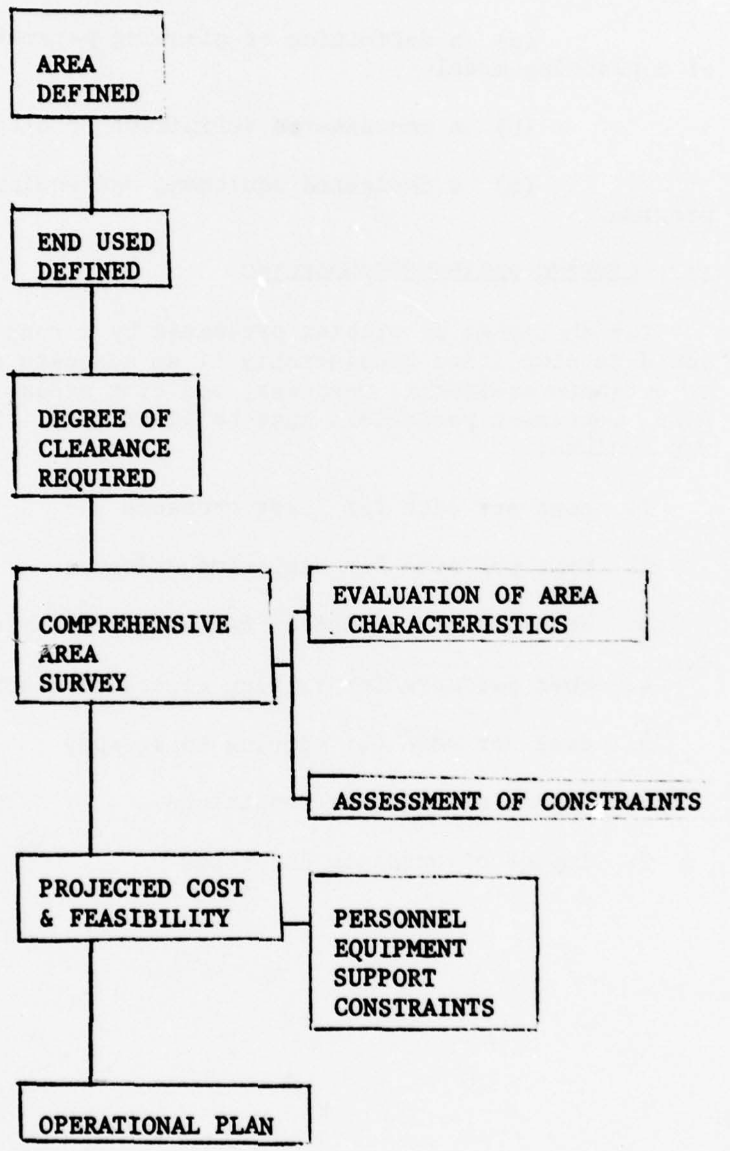
II. PLANNING PARAMETERS/MODELING

The challenge or problem presented by a range clearance operation could be simplified considerably if an adequate plan could be formulated to estimate equipment, manpower, and time needs. To formulate such a plan, pertinent parameters must be identified. Some of these parameters may include:

1. cost per acre for inert ordnance
2. cost per acre for explosive ordnance
3. cost per acre based on degree of contamination
4. cost per acre for varying clearance depths
5. cost per acre for varying topography
6. impact of climatic conditions
7. impact of ordnance dud rates

These parameters are used or developed in the following manner during the planning phase.

GENERAL RANGE CLEARANCE PLANNING



The planning phase, which is a continuing process, involves the following general considerations that must be addressed for any range clearance operation:

1. The area to be cleared must be defined. It may include both land and water areas.

2. The immediate and future use of the land must be defined. This factor will have the greatest impact on the ultimate cost and effectiveness of the operation in the overall plan.

3. A reasonable determination of the degree of clearance required is made. This can vary from "surface only" to clearance at substantial depths.

4. A comprehensive area survey must be accomplished and data logically assessed. The total area and excavation requirements will dictate the overall effort and costs.

5. During the on-site survey and records study certain factors relating to area characteristics must be evaluated in detail. These characteristics include:

a. Terrain features: These will influence accessibility and the use of equipment.

b. Vegetation/Ground cover: The degree of growth will greatly influence reconnaissance and restoration requirements should removal be necessary.

c. Soil composition: This affects penetration depth of the ordnance and the use of clearance equipment. In the case of marshlands, unique clearance problems need to be addressed.

d. Ordnance contamination: An estimation of the type, amount and location of ordnance contamination is of prime importance.

6. Input from the comprehensive area survey will provide a basis on which to assess technical and operational constraints. Significant constraints which must be addressed include:

a. Environmental impact of possible clearance techniques. All clearance plans must address the consequences of ground cover removal, destruction of vegetarian and animal life, erosion, and pollution.

b. Operational safety of personnel.

c. Equipment survivability.

d. Feasibility of utilizing clearance equipment.

e. Effectiveness of location/detection equipment which can be severely limited in a highly magnetic area.

7. The projected cost and most feasible approaches are determined based upon all the available data and best estimates. The highlights of this evaluation can be summarized under the following major categories:

a. Approach Suitability - With regard to the area concerned, are desired results achieved?

b. Approach Feasibility - Considering area constraints, are the means and manpower available to achieve the desired results?

c. Approach Acceptability - From the standpoint of the cognizant military agency, the civilian populace, political/legal aspects and costs, can desired results be attained?

8. Trade-offs are then made with regard to time, costs and available resources and an Operational Plan is formulated.

A brief look at several range clearance projects will point out some of the major considerations which will continually be significant elements in future planning.

1. Frankford Arsenal: As a result of the closure of Frankford Arsenal and the requirement to decontaminate the facilities, the Naval Explosive Ordnance Disposal Facility (NAVEODFAC) responded to a request to conduct a site survey. During October 1977, a survey team conducted the survey utilizing the AN/PSS-11 and the MK 22 MOD 0 Ferrous Ordnance Locator. Significant factors resulting from the survey and the operation follow:

a. The primary areas of concern were the parade grounds and adjacent built-up areas. The parade grounds area was approximately 1.5 acres and adjacent areas amounted to 4.5 acres.

b. Using a one meter spacing interval, over 3,000 contacts were made using the locators.

c. Over 500 contacts were hand excavated or uncovered with the use of a back-hoe to the depth of 30 inches.

d. Examples of the items recovered included nails, circular metal discs, pipes, an old building foundation, and two inert cannonballs.

e. No hazardous material was found.

Lessons learned include:

a. An effective site survey was severely hampered by the presence of the non-UXO material.

b. Built-up areas including buildings, underground utilities and pavement precluded conducting a reliable search operation.

c. Historical records of the prior land usage were inadequate or non-existent.

2. Kahoolawe Island: Located 94 miles southwest of Honolulu, the island consists of 28,766 acres. It has been used as a target complex since 1941. An extensive study was conducted in 1976 to determine the feasibility and related costs of clearing the island of unexploded ordnance. Highlights of the survey follow:

a. Approximately six percent of the island was subjected to detailed surface reconnaissance, and divers conducted an underwater survey of pre-selected areas along the aircraft run-in lines and surface firing zones.

b. The survey revealed surface contamination of various types of UXOs amounting to a density of 0.34 items/acre.

c. Subsurface and underwater contamination could not be determined. Poor visibility and weather prevented a systematic underwater survey although numerous UXOs were sighted.

d. The terrain characteristics were:

(1) Sixty percent of the island is covered with vegetation.

(2) Thirty percent is barren dust with severe erosion forming deep gullies.

(3) Elevations range up to 1,477 feet; some slopes contain gulches 50 to 200 feet deep.

Conclusions of the study point out that:

a. Ten percent of the island area is unaccessible and cannot be feasibly cleared.

b. Clearance costs were estimated as a function of land use alternatives and clearance options.

c. The presence of large explosive filled munitions warrants the use of special equipment and remote controlled vehicles.

d. The degree of subsurface and underwater contamination could not be determined and must be further investigated.

e. Significant technology support effort is needed to develop specialized range clearance systems.

f. Inadequate records exist on the island use as an ordnance impact area.

g. Information is inadequate with respect to the degree of malfunctioned ordnance or duds experienced, amount of ordnance purposely dropped in the unarmed condition and the level of operator error (that is: pilot/gunner/ordnanceman) resulting in munitions impacting in the unarmed condition.

h. Subsequent site surveys revealed that the existing locations/detections systems were ineffective due to the high ambient magnetic signatures caused by the volcanic material throughout the island.

3. Culebra Island: Located approximately 20 miles east of Puerto Rico, the northwest peninsula of the island (containing 320 acres) and adjacent smaller islands have been used as an aerial and naval target area since 1936. The following factors would apply to a clearance operation:

a. Records indicate that over 750,000 rounds had been fired on the peninsula up until January 1972.

b. The terrain has steep slopes toward the sea on all sides.

c. Soil is hard laterite with extensive rock content.

d. Extensive UXO contamination on land and underwater is quite evident.

e. An extensive range clearance feasibility survey and cost study need to be conducted.

f. Decontamination of underwater areas will be severely hampered by environmental constraints.

4. Putnam Target Range: This range clearance project has just been completed. The 76-acre range is located 32 miles south of Naval Air Station, Jacksonville, Florida. The land has been used as a bombing target since 1943. Commencing in October 1977, the Navy started an extensive decontamination operation to meet the existing agreements set forth in the lease with Union Camp Corporation (the land owner) which is "to return the land to its pre-lease condition". The following survey factors are important:

a. A viable operational plan was formulated by EODGRUTWO based upon an extensive site survey.

b. The degree of clearance was established at 12 inches based upon the projected land use as a tree-farming area.

c. Sample sections were excavated and analyzed to substantiate the existing records which stated that the area was not used for live munitions.

d. The clearance operations started based upon the reasonable expectation that the munitions in the area consisted primarily of practice bombs (some of which contain MK 4 smoke signals), and aircraft rockets with inert warheads.

A summary of operations to date shows that:

a. Large scrapers and bulldozers were rented from a local contractor to perform the earthmoving tasks.

b. MK 9 Ordnance Locators were used as the location/detection system.

c. Over 100,000 complete items have been recovered to date.

d. All material found is being transported to Rodman Target (south of Putnam) for final disposition at a later date.

e. The Surface/Shallow Subsurface Clearance Vehicle (SSCV) presently in the exploratory stage at NAVEODFAC was utilized as part of the developmental testing.

f. A comprehensive report and technical film are being generated for wide distribution.

The following lessons were learned:

a. The cost of range clearance is certainly substantial. Although actual final figures have not been assessed, it is estimated that clearance cost $10,000 per acre.

b. The cost would be substantially higher if the area was contaminated with live ordnance.

c. More cost effective mechanical earthmoving/recovery equipment is needed.

d. The effects of the climate severely limited operations. Seasonal rain caused substantial access problems for both personnel and heavy equipment which resulted in slippage of the scheduled completion date.

The following facts summarize experience gained to date:

1. Adequate range usage and past clearance records do not exist.

2. Environmental impact and restoration effort will be very restrictive.

3. Personnel safety must be given a high priority.

4. Equipment survivability greatly influences effectiveness.

5. Operations in adverse climates limits equipment and personnel effectiveness.

6. Operation in a chemical ordnance environment may be required.

7. Effectiveness of location/detection systems are severely limited or useless in scenarios or conditions that:

a. contain highly magnetic soils.

b. are highly contaminated with debris.

c. are in close proximity to major improvements.

d. contain non-ferrous cased munitions.

8. The technology base must be expanded to meet both immediate and future requirements.

III. CLEARANCE CRITERIA FOR RANGES AND RELATED LAND USE

A Introduction

The U. S. Government has been giving continued attention to the necessity of clearing for non-military use ranges and other areas used by the military services. A Department of Defense inventory, on an individual department basis, has, as stated previously, been established within the three military departments. Special studies have been initiated to determine the magnitude of the clearance problem and the techniques involved and the nature of the clearance required for specific types of land use. The Departments of the Army and Navy have completed two major studies; the Department of the Air Force has investigated the feasibility of maintaining a centralized computerized record of the military use of ranges so that when clearances are directed, the task of the Explosive Ordnance Disposal personnel can be simplified.

The two principal studies undertaken to date indicate that a complete clearance of ranges to a depth greater than 15 centimeters is not generally cost-effective. It was further indicated that clearance of wetlands is not feasible and that ranges previously used for chemical munitions posed additional problems which would require continued study. As far as equipment was concerned, it was determined that better location systems and special clearance vehicles would be required if clearance of ranges was to be undertaken in a cost-effective manner.

B. Department of the Army Study

1. Background

A detailed study of range clearance problems were assigned to the Army Corps of Engineers who determined that clearances of Army ranges would have to be addressed within the following three constraints:

a. Seven clearance standards to be established and to be associated with specific land uses. (These would be related also to available equipment and operational procedures).

b. Clearing standards to be utilized with a major clearance plan must be related to the ultimate land use.

c. Economic feasibility or environmental aspects might preclude decontamination of certain ranges.

In order to obtain a full understanding of the problems inherent in establishing alternative land uses for a range area, it was decided to select six Army installations. Data was then obtained on the following facets of the proposed clearance operations to permit other land uses.

a. Tabulation of the known UXO and chemical contamination of the site.

b. The nominal penetration depth of the munitions involved relative to the geological data of the site was determined, using existing munition terminal ballistics data.

c. Identification of detection and clearing procedures relative to the munitions identified and general site topography.

d. The estimated extent and cost of the work involved to effect clearance of a range.

e. The problems related to chemical detection and neutralization if this was a factor.

f. A spectrum of land uses alternatives is considered for each range, and

g. Minimum testing requirements were established relative to location/detection equipment that might be required in a range clearance operation to establish confidence in the final clearance certificate.

2. Recommended Clearing Standards

The Corps of Engineers recommended that seven discrete clearing standards be established, ranging from "no-clearing" to "deep depth" and "localized clearance". These standards were identified as follows:

a. No-Clearing - Areas in this category will be fenced and posted with warning notices and will be used as military range and disposal areas.

b. Surface Clearing - Visual inspection and ordnance locators will be used to remove all munition items located at or very close to the surface. The areas will be used for wilderness parks, sanitary land fills and grazing cattle.

c. Minimum Depth - A windrower or mechanically propelled rake assisted with a rock picker will be used to guarantee removal of munition items down to a depth of 15 centimeters. Representative land use of this type of clearance would be "limited agricultural."

d. Shallow Depth - The AN/PSS-11 Locator would be used to detect munitions and metal fragments. Any scrub growth would be removed in order to ensure that munition location was effectively accomplished. After shallow-depth clearance, the land could be used for unlimited agricultural utilization, etc.

e. Medium Depth - All UXO's would be removed up to a depth of 4.5 meters, following any necessary surface or shallow clearance. If an analysis showed that the clearance depth exceeded the known UXO penetration depth, then unlimited use of the land would be permitted.

f. Deep Depth - Similar to clearing standard above, except that UXO's would be removed to 6.0 meters.

g. Localized Area - In this case, limited areas would be cleared and then overlaid with sufficient earth fill to meet the depth requirements for the land use proposed. Unlimited use of the land would be permitted but excavation below the certified final cleared depth would be prohibited.

3. Conclusions of the Corps of Engineer's Study

Major conclusions of the study completed by the Army Corps of Engineers indicated that clearing standards d, e, f, and g are much too expensive for application to large range areas. In addition, the clearance of wetlands was not considered feasible on a cost-benefit basis and, when chemical items were involved, further study of the unique safety problems was required before clearance could be initiated.

C. Department of the Navy Study

1. Background

The Naval Sea Systems Command ordnance clearance study encompasses a total decontamination program relative to land and sea ranges, as well as a review of equipment requirements and estimates of time and costs for clearance operations. The study highlighted the following problems:

a. Over the past decades, adequate records have not been maintained for one reason or another relative to types of munitions and quantities involved.

b. UXO location capabilities need to be enhanced.

c. Mechanical equipment requirements to support EOD clearance operations are not supported by in-service equipments.

d. Severe military manpower restraints preclude early completion of overall clearance operations.

As a result of this study, a number of projects were proposed to overcome the deficiencies enumerated above.

2. Current Requirements

A number of requirements exist for overcoming the deficiencies in current range clearance capabilities. These include:

a. A study on ways to control range utilization associated with computerized record-keeping of munition testing.

b. The study of multi-sensor location system with automated data processing so as to improve the discrimination against false targets and permit reliable location of non-metallic and non-ferrous munitions at greater depths.

c. Development of a family of equipment for clearance of ordnance. This will comprise two basis systems; one for shallow subsurface clearances (a prime mover, digger/sorter and a collector would be developed) and another for special recovery (a tree-digger, clamshell digger and light-weight winch-drawn bulldozer would be required).

D. Concluding Remarks

A comparative study is underway within the DOD to develop the most cost-effective means of clearing ranges of munitions which may be hazardous relative to projected land use requirements. It has been determined that there is no simple way to effect one hundred percent decontamination of range areas. The application of the clearing standards relative to projected land use in association with the development of specialized equipment will go a long way to ensuring that only a reasonable proportion of the DOD resources will need to be allocated to decontaminate ranges scheduled for conversion to other land usage categories.

It is recommended that the following clearance and land use criteria be established for land returned to the private sector or non-defense elements of the Federal Government.

1. Wildlife habitat: fence and post

2. Wilderness area: surface clearance

3. Limited agriculture: clearance to depth of 12 inches

4. Unlimited farming: clearance to depth of 24 inches

5. Unrestricted use to given depth: clearance to stated depth or the lay-down of controlled depth of fill.

PART II: TECHNOLOGY

IV. EQUIPMENT AND EQUIPMENT DEVELOPMENT SUPPORT NEEDS

A. Technical Problems

The process of clearing a range involves many different basic technical areas. These include:

1. Reconnaissance
2. Location/Detection
3. Surface Clearance
4. Subsurface Clearance/Access
5. Munition Transport
6. Massed Munition/Hardware Disposal

Superimposed on these technical areas of effort are constraints. These include:

1. Technology state-of-the-art
2. Environmental Impact Assessment
3. Operational Hazard
4. Degree of Clearance Required
5. Time to accomplish effort
6. Certification Requirement

The specific technical problems encountered in each of the technical areas depend on the specific clearance operation to be conducted and the impact of the contraints that are imposed.

1. Reconnaissance

The success of any clearance operation depends largely on the extent to which reconnaissance is conducted. Planning of the requirement for and the allocation of equipment and manpower is dependent on thorough reconnaissance. Reconnaissance can be conducted in a number of combinations of ways using manual or automatic and continuous or discrete methods. Old or obsolete ranges to be cleared would involve using discrete manual methods. Active ranges can incorporate continuous automatic methods. In any case, reconnaissance must provide adequate planning information.

Based on reconnaissance information and resource or time limitations, a realistic plan can be formulated and executed. Reconnaissance techniques can vary from a simple visual observation to the use of advanced sensors and sensor platforms. Examples of sensors that may be used include:

1. Closed circuit TV (particularly low light level capability)
2. Infra-red sensors
3. Photographic sensors

These may be mounted on surface or airborne platforms. The platforms on the surface may be stationary or mobile. Improved reconnaissance equipment and techniques may appear to be costly, but the initial cost can be recovered through more efficient planning and resource allocation that is achieved.

2. Location/Detection

Location/detection of buried ordnance presents a variety of technical problems relating to environmental and clearance depth requirements. The clearance may be on a surface range requiring detection or location to a specified depth. It may also be in an underwater area requiring detection of everything on the underwater surface or buried beneath the underwater surface. The three biggest technical problems are:

a. State-of-the-art of sensor technology (both ferrous and nonferrous sensors)

b. Positioning information (programming location paths or returning to specific locations on the surface or underwater)

c. Information processing (real time processing and target classification information)

Location/detection sensors may be used individually or in multiple sets (similar or different sensors) and in hand carried or towed configurations. The exact configuration required would be based on reconnaissance information.

3. Surface Clearance

Surface clearance may be the only requirement for certain clearance operations or it may be the first step in a deep clearance operation. It may be conducted in an unsophisticated manner (walking over the surface and picking up items) or a sophisticated remote manner. As the hazard or degree of contamination increases (hazard may be caused by complex mechanisms or deteriorated mechanisms), the need for sophistication also increases. For heavily contaminated areas, sophistication is the only cost effective approach.

As more and more complex and costly equipment is used, the need increases for effective armor material to protect the capital investment. There is a tradeoff between remote control and expendable equipment that is possible, but the nature of the equipment may not allow such a tradeoff.

4. Subsurface Clearance/Access

Some clearance operations will require clearance below the surface. This subsurface clearance may be conducted in heavily contaminated areas requiring movement of a large amount of soil or it may be conducted against individually located items (access). The equipment required for these different operations is vastly different. One requires a heavy duty piece of equipment with the capability to dig, sort, convey and store or transport. The other requires a much simpler digging device. The nature of the subsurface clearance/access operation will be determined based on reconnaissance information.

5. Munition Transport

The material recovered during a clearance operation must be transported to a site for examination, classification, and sorting. These functions are usually not performed during the clearance operation unless the operation is an unsophisticated manned operation. Transport requirements vary from simple trucks for inert or safe material to vented or total containment vessels for hazardous items to total containment with scrubbing for hazardous toxic items. The nature of the transport operation is determined during the reconnaissance operation.

6. Massed Munition/Hardware Disposal

After cleared items have been classified and sorted, they must be disposed of in a proper manner. Disposition may range from simple sale of metallic junk to burning or sympathetic detonation of explosives and combustible materials to the complex neutralization of hazardous or toxic materials. Disposal will normally be conducted away from the vicinity of the actual clearance operation. Some consideration must be given to the environmental impact of explosive or thermal disposal. In some cases, a totally contained disposal facility that includes disassembly, thermal disposal with scrubbing, and chemical neutralization with scrubbing may be required. The reconnaissance operation will provide information necessary to plan final disposition.

7. Constraints

The technical impact of constraints imposed has been mentioned in some cases, but they have much wider impact then already discussed. State-of-the-art of sensor capability is of particular concern when attempting to locate nonferrous items. Location of ferrous materials by measuring changes in the earth's magnetic field caused by ferrous objects is feasible. Location of nonferrous objects using active acoustic, microwave or electromagnetic technology has not been adequately demonstrated. Classification of buried targets (under the surface or underwater) has not been demonstrated. The use of combinations of several sensors has been proposed but not demonstrated. Environmental impact considerations

pose a technical constraint on several areas. Deep clearance operations disturb the surface growth and underlying layers of soil. Heavy contamination cannot be removed without such disturbance. Thermal and explosive disposal operations are generally essential to clearance operations. They tend to be the most cost effective methods of destroying large amounts of explosive material. Operational hazards are posed by clearance of active ranges, the presence of badly deteriorated explosive items, by the presence of toxic materials, or by the presence of complex items. Varying clearance depth requirements posE location/detection problems. For shallow clearances, sensors with limited detection capability are required. Sensitive sensors complicate the operation by detection of deeply buried items. Any legal certification requirement poses severe technical problems. Total clearance to specified depths is not possible in a timely or cost effective manner. Location/detection and surface/subsurface clearance techniques are not totally effective without repeated application.

B. Summary of Technical Problems

The major technical problems confronting range clearance operations are:

1. Conducting adequate surveys to plan resource allocation

2. Coping with limitations of sensors technology

   a. Detection range for ferrous objects

   b. Location of nonferrous objects

3. Providing adequate location information processing

4. Providing automated surface and subsurface clearance methods

5. Providing safe munition transport and disposal equipment

6. Coping with environmental impact assessment and restrictions

7. Providing safe methods for handling badly deteriorated or toxic items

8. Providing clearance certification

C. Active Clearance Equipment and Technology Projects Related To Range Clearance

The joint service EOD program currently includes a number of projects aimed at range clearance or related requirements. These projects follow:

1. Location/Detection

a. NAVEODFAC is currently developing a hand-held ferrous ordnance locator based on a cesium vapor magnetometer sensor. It provides a significant improvement over existing magnetometers used for location of buried or underwater ordnance. The same sensor is being considered for use in a towed multiple sensor configuration for surface or underwater use.

b. An underwater Area/Point Search System (APSS) is being developed to search for and isolate the location of underwater ordnance. It consists of the following subsystems:

(1) Navigation/Data Handling Subsystem - A line of sight radio frequency device is used to guide search sensors along programmed search tracks or to return to predetermined points in the search area. The system can be programmed to coordinate position data with search sensor information and provide location of target ordnance items. The system has been operated successfully from large and small boats, helicopters, and surface vehicles.

(2) Underwater Towed Sensors - Side scan sonar and cesium vapor magnetometer sensors have been configured for towing underwater. The systems have been operated successfully in a variety of operations searching for ordnance items and aircraft.

(3) Diver-Held Magnetometer - The cesium vapor magnetometer is being configured for hand-held underwater use. It will be used by divers to isolate the location of targets previously identified by towed sensors.

c. Several studies have been planned to enhance EOD range clearance capability. These include evaluations of various active ordnance location techniques. Among these are the microwave or radar technique and the electromagnetic sensor. These techniques have been used successfully to locate geological faults but must be further studied to determine applicability in the ordnance location role. A demonstration of a surface towed multiple sensor magnetometer is also being studied. The sensor platform and data processing components are being designed for the demonstration.

2. Surface Clearance

A project is being pursued to provide radio remote control capability for bulldozers. Initial feasibility has been demonstrated and a working model has been built for TD-20 class bulldozers. The remote control unit has been demonstrated using the TD-20 as a prime mover for towed equipment during actual range clearance testing.

3. Subsurface Clearance/Access

A Surface/Subsurface Clearance Vehicle (SSCV) test platform has been built and tested for range clearance application. The design is based on the "rock picker" concept used in the construction industry. Two models were built to test range clearance concepts. The SSCV, which can dig to a depth of 18 inches on a single pass, has been tested on actual range sites in Northern Florida (Putnam and Pinecastle Ranges). The tests indicate that further refinements must be made to the basic platform to achieve maximum effectiveness.

4. Munition Transport

Total Containment Vessels (TCVs) large enough to contain either ten pounds or forty pounds of high explosive have been fabricated and successfully tested. The vessels are reusable so they can be used for transportation and disposal where open burning or detonation is not possible.

In summary, projects are currently being conducted to:

1. Develop improved surface and underwater ferrous item sensors.
2. Develop navigation and data handling systems.
3. Identify new nonferrous sensor technology.
4. Provide remote controls for existing equipment.
5. Develop a surface/subsurface clearance vehicle.
6. Develop total containment vessels.

D. Additional Technology and Equipment Required

To provide more complete range clearance capability, additional equipment/technique development is needed in addition to what is currently being developed. The equipment development program would include the following:

1. Location/Detection

a. Towed multiple land sensor arrays

b. All-up borehole locator system

c. Improved electromagnetic and microwave sensors for nonferrous munitions.

2. Surface Clearance

Remotely operated hardened surface clutter "sweepers" with ordnance sorting capability.

3. Subsurface Clearance/Access

Remotely operated, remotely towed hardened subsurface clearance vehicle.

4. Munition Transport

a. Vented vessel with capability of withstanding detonations.

b. Total explosive containment vessel with a scrubber system.

5. Munition Disposal

Portable contained disassembly and burnout facility for explosive items containing high explosive.

The end result of development of equipment will be to establish a central point for supporting the planning and conducting of clearance operations. The equipment required to support operations from a central location follows:

a. Three towed sensor arrays (combined magnetometer and electromagnetic).

b. Three hand-held active locators for nonferrous materials.

c. Three hand-held passive locators for ferrous materials.

d. One earth auger.

e. One surface sweeping vehicle to remove surface fragmentation.

f. Three subsurface clearance vehicles providing 24" depth capability.

g. Two vented containment vessels.

h. Two portable total containment vessels.

i. One portable disposal facility.

To provide this capability funding it at a level of $3,000,000 per annum for three years is initially required. Thereafter, $2,000,000 per annum is needed to maintain a technical support pool of 20 personnel and also to provide for equipment maintenance and special equipment rental.

V. OVERALL SUMMARY

The summaries of the range clearance problem by Military Departments have identified three categories of clearance:

(1) Clearance of ranges to be returned to the private sector.

(2) Clearance of ranges to permit their continued use for training and for test and evaluation of new weapon systems, and

(3) Clearance of areas returned to the private sector which were cleared and covenanted for limited types of use.

Clearance encompasses all types of terrain in all types of climate and both time and natural forces modify the clearance problem. In this latter regard, an open range abandoned for 20 years may be a forest when clearance is proposed, similarly buried ordnance not found in a surface sweep may be exposed by erosion or land uses not anticipated when the land was sold.

Range clearance is automatically assigned within the military services to the EOD forces using the equipment normally provided to support routine military EOD requirements, such as normal individual unexploded bomb incidents. When a large range is to be cleared, the EOD forces have been ill-equipped from the resource standpoint often requiring augmentation with engineering equipment and personnel to handle the earth moving aspects. The problem of detection and location of hazardous objects is compounded by the false targets created by surface shrapnel.

Ranges typically have been selected on the basis of being land nobody else wanted or were purchases to complement an existing installation. The mobility of society today has resulted in isolated ranges being invaded by non-DOD personnel and also in formerly valueless land being made economically attractive to real estate developers. We must recognize that DOD must develop a firm set of criteria for clearing and disposing of land in a manner which will best serve the public interest relative to long term uses of the land.

To aid military personnel concerned with range clearance, planning methods, clearance standards, and equipment support must be provided.

To aid on planning clearance operations, the following are important:

1. The Military Services must maintain for each range archival data on the utilization of all weapons and fuzes. Full nomenclature (including MK and Mod data) is required.

2. The development and in-service engineering agent must maintain accurate dud-rate for all weapons and fuzes.

3. Any weapons which have been jettisoned in an unarmed condition during air, land, or naval operations or exercises must be logged.

In addition, the following action is required relative to clearance standards:

1. Insofar as clearance standards and land usage are inseparable, it is necessary for the Department of Defense (DOD) and General Services Administration (GSA) to agree jointly on clearance and land use standards. Standards for clearance of active-ranges are also required.

2. Additionally, the legal liabilities of the statistical risks associated with anything less than complete clearance must be identified when land is declared excess.

Equipment support would be aided by the following actions:

1. To facilitate equipment design by the Department of the Navy, all Military Services should forward their technical requirement for range clearance to the NAVEODFAC.

2. Listing of ranges together with relevant topographical and geological information would assist the developers.

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APPENDIX A

ADDITIONAL INFORMATION REGARDING

MILITARY TARGET AREAS

ARMY TRAINING INSTALLATIONS

Installation	Total Acreage	Target Range Acreage	Status
Fort Belvoir & MCB Qauntico, VA	9,237	8	Active
Fort Benning, GA	181,835	33,000	Active
Fort Bliss, TX	1,122,835	770,962	Active
Fort Bragg & Camp Mackall, NC	137,331	27,726	Active
Fort Campbell, KY	105,397	22,809	Active
Canal Zone	113,782	1,000	Active
Fort Carson, CO	137,391	21,000	Active
Fort Chaffee, AR	71,963	20,000	Active
Fort Devens, MA	9,414	1,000	Active
Fort Dix, NJ	31,791	16,400	Active
Fort Drum, NY	107,265	39,000	Active
Dugway Proving Grd, UT	840,911	58,000	Active
Fort Eustis w/Fort Monroe & Fort Story, VA	8,305	400	Active
Fort Gordon, GA	55,648	13,722	Active
Fort Greeley, AK	639,055	141,000	Active
Fort A.P. Hill & Fort Lee, VA	77,028	26,671	Active
Fort Hood, TX	216,915	62,000	Active
Fort Hunter-Liggett, CA	166,325	10,000	Active
Fort Huachuca, AZ	112,811	6,672	Active
Fort Irwin, CA	642,820	49,000	Active
Fort Jackson, SC	52,596	21,928	Active
Fort Knox, KY	110,164	45,710	Active
Fort Leonard Wood, MO	68,563	19,000	Active
Fort Lewis, WA	86,759	10,625	Active
Fort McClellan & Anniston, AL	45,553	3,957	Active
Fort McCoy, WI	59,778	7,656	Active
Fort Meade, MD	13,486	6,370	Active
Fort Ord & Presidio of Monterey, CA	28,360	7,000	Active
Fort Pickett, VA	45,198	8,000	Active
Fort Polk & Peason Trng Area, LA	198,214	30,000	Active
Fort Richardson, AK	71,372	9,000	Active
Fort Riley, KS	101,001	28,000	Active
Camp Roberts, CA	42,539	13,000	Active
Fort Rucker, AL	58,492	9,700	Active
Camp Shelby, MS	135,419	Unknown	Active
Fort Shafer w/Schofield, Pohakuloa and other Hawaii Installations	179,277	62,626	Active
Fort Sill, OK	128,581	30,190	Active
Fort Stewart & Hunter, GA	284,673	128,250	Active
Fort Wainwright w/Yukon Trng Area, AK	655,946	232,000	Active
Whitesands, NM	1,754,023	540,000	Active
Yakima Firing Center, WA	263,131	29,158	Active
Yuma, AZ	1,043,000	296,000	Active

ARMY TRAINING INSTALLATIONS

Installation	Total Acreage	Target Range Acreage	Status
Grafenwohr, Germany	41,500	Unknown	Active
Hohenfels, Germany	57,500	6,180	Active
Wildelecken, Germany	17,500	3,950	Active

ARMY INSTALLATIONS DECLARED EXCESS

Installations	Total Acreage
Blossom Point Testing Facility, MD	2,000
Castner Range, Fort Bliss, TX	8,200 (1,200 cleared)
Fort Detrick, MD	no information
Fort Lee, VA	2,354
Fort George G. Meade, MD	6,854
Rocky Mountain Arsenal, Denver, CO	no information
TOTAL	19,408

NAVY TARGET AREAS

Naval District/Overseas Area	Land Acreage
First	628
Third	7
Fourth	300
Fifth	55,253
Sixth	31,356
Eighth	728
Ninth	None reported
Eleventh	2,146,343
Twelfth	26,630
Thirteenth	48,154
Fourteenth	28,874
Fifteenth	0
Washington, D.C.	7,002
Atlantic	14,813
Pacific	8,145
TOTAL	2,368,233

Not included in the total acreage are areas that were formerly under the cognizance of various Navy and Marine Corps commands, and which are still contaminated with ordnance, but are no longer under Department of the Navy control. Because many areas were returned to private and public ownership decades ago, a comprehensive assessment can probably never be made.

Navy/MARCORP Former Ranges Returned to the Private Sector

Area Identification	Former Cognizance	Land Acreage	Water Acreage
Seal Island Target	NAS, Brunswick, MA	65	*
Townsend Target	NAS, Glynco, GA	4,000	0
Pensacola Impact Ranges	NAS, Pensacola, FL	4,000	*
Belleair Beach, Tampa	Sixth Naval District	0	43
Plano Trubuco Target Range	MCAS El Toro, CA	503	0
Mojave "C" Target Range	NWC China Lake, CA	21,756	0
Kodiak Demolition Range	NAVSTA Kodiak, AK	31	0
Pasco Impact Area	NAS Whidbey Is, WA	5,000	0
Kauna Point Range	NAS Barbers Point, HI	2,198	*
Molokini Island**	NAS Barbers Point, HI	27	*
Mokuhooniki Island***	NAS Barbers Point, HI	13	*
Culebra Target Complex	AFWR, Tenth Naval District, PR	648	*
		38,241	43*

* The extent (acreage) of ordnance contamination in the contiguous waters cannot be determined at this time.
** Molokini Island is 4.3 n.m NNE of Ule Point, Kahoolawe, and in the channel between Kahoolawe and Maui.
*** Mokuhooniki Island is 1.5 n.m SSE of Cape Halawa, eastern tip of Molokai.

CONTINENTAL U. S. AIR FORCE RANGES

Air Force Base	Location	Area	Status
Avon Park	Florida	101,020	Active
Badlands	Senic, SD	2,487	Excess-Unclearable
Blair Lake	Fairbanks, AK	33,964	Active
Claiborne	Foresthills, LA	25,972	Active
Cuddeback Lake	Tohannisburg, CA	7,584	Active
Dare County	Stump Pt, NC	46,652	Active
Hill	Wendover, UT	351,539	Active
Luke	Gilabend, AZ	2,673,467	Active
Matagorda	Port O'Connor, TX	50,935	Excess-Cleared
Melrose	New Mexico	22,087	Active
Nellis	Indian Springs, NV	3,001,907	Active
Poinsett	Wedgefield, SC	8,039	Active
Sailor Creek	Bruneau, ID	111,414	Active
Shipshoal	Cape Charles, VA	1,942	Excess
Smoky Hill	Brookville, KS	33,878	Active
Wendover	Wendover, UT	572,588	Active
	Totals	6,990,111	Active
		55,364	Excess
	Grand Total:	7,345,475	

OVERSEAS AIR FORCE RANGES

Designation	Location	Area	Status
Siedenburg Air Range	Muehlausen, GY	680	Active
Ide Suna Jima Air Range	Naha, Japan	54	Active
Tori Shima Air Range	Naber, Japan	10	Active
Koon-ni Air Range	Koon-ni	4,907	Active
	Total	5,654	

RANGES AIR FORCE EOD IS RESPONSIBLE FOR CLEARING

Range	Location	
Falcon Range	Oklahoma	
Oscura Range	New Mexico	
Balboa West Range	Canal Zone	
Crow Valley Range	Philippines	
Ie Shima Range	Okinawa	
Eglin Ranges	Florida	
Oklahoma Range	Alaska	
Edwards Ranges	California	
Red Rio Range	New Mexico	
Brookville Range	Kansas	
Warren Grove Range	New Jersey	(National Guard Range)
Ft Drum Range	New York	"
Camp Attabury Range	Indiana	"
Jefferson Proving Ground Range	Indiana	"
Camp Grayly Range	Michigan	"
Hardwood Range	Wisconsin	"
Ft Carson Range	Colorado	"
Razorback Range	Arkansas	"
Camp Selby Range	Mississippi	"
Salinas Range	Puerto Rico	"

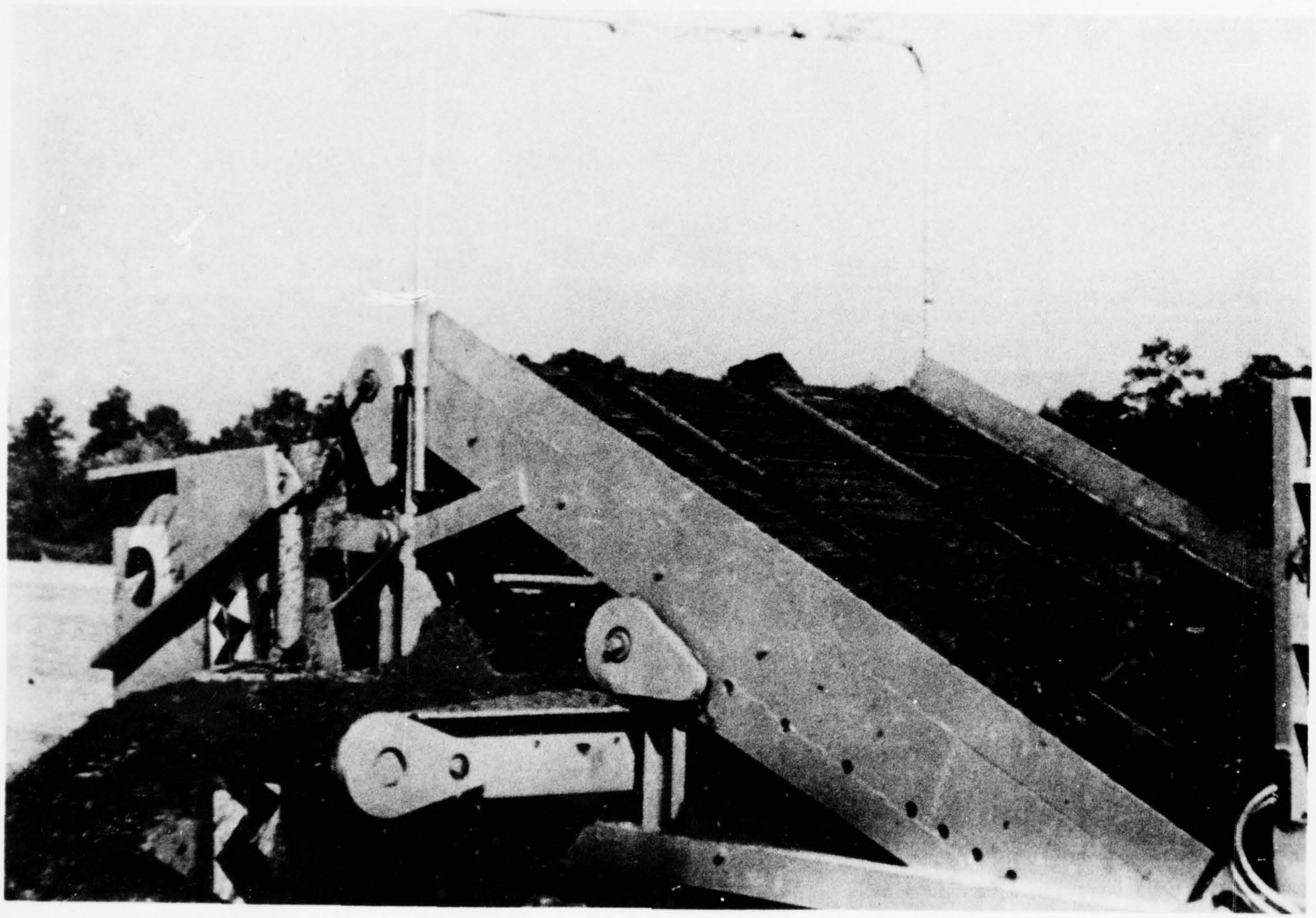
APPENDIX B

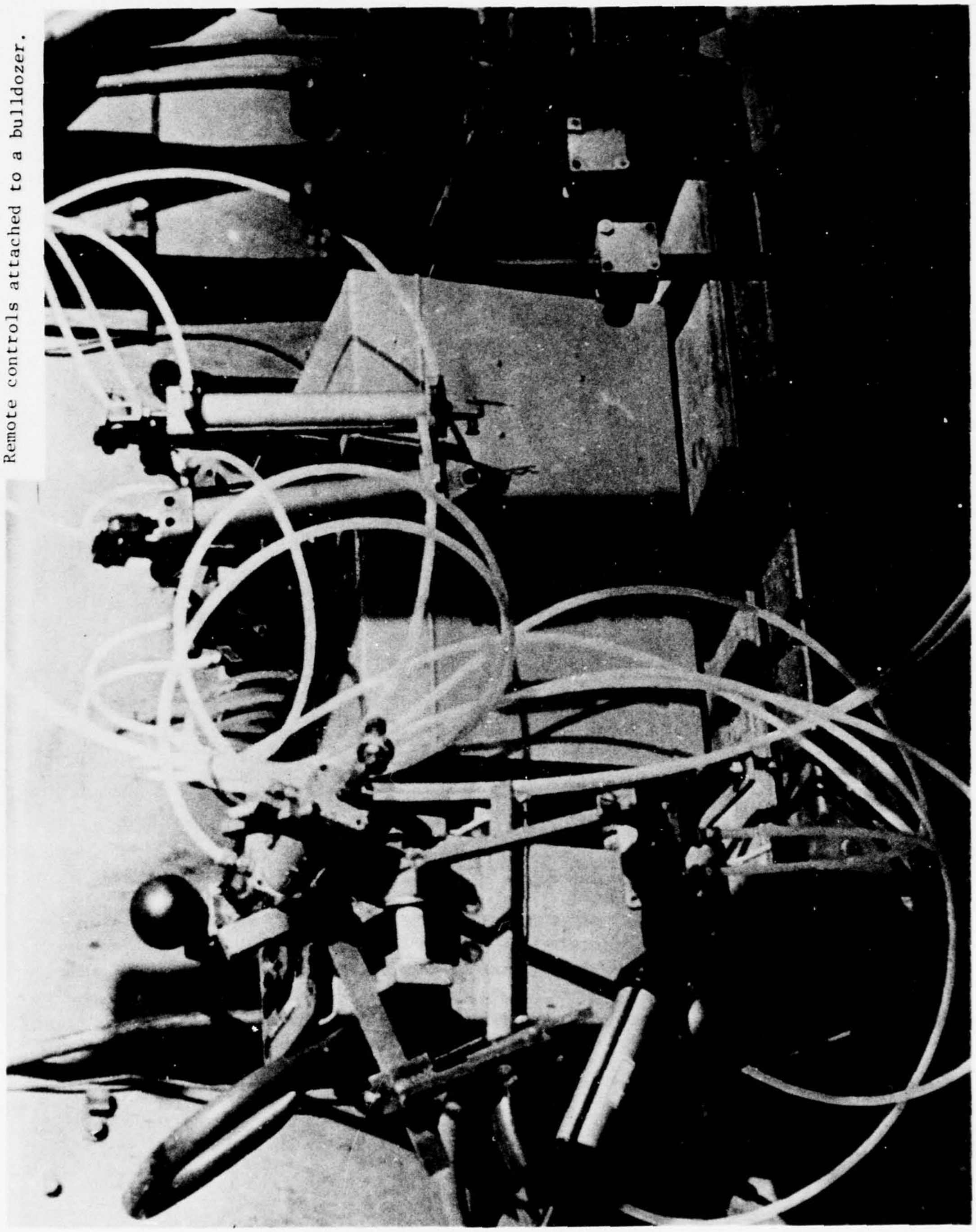
EQUIPMENT ILLUSTRATIONS

British Combat Engineering Tractor (CET) can be used for range clearance operations.

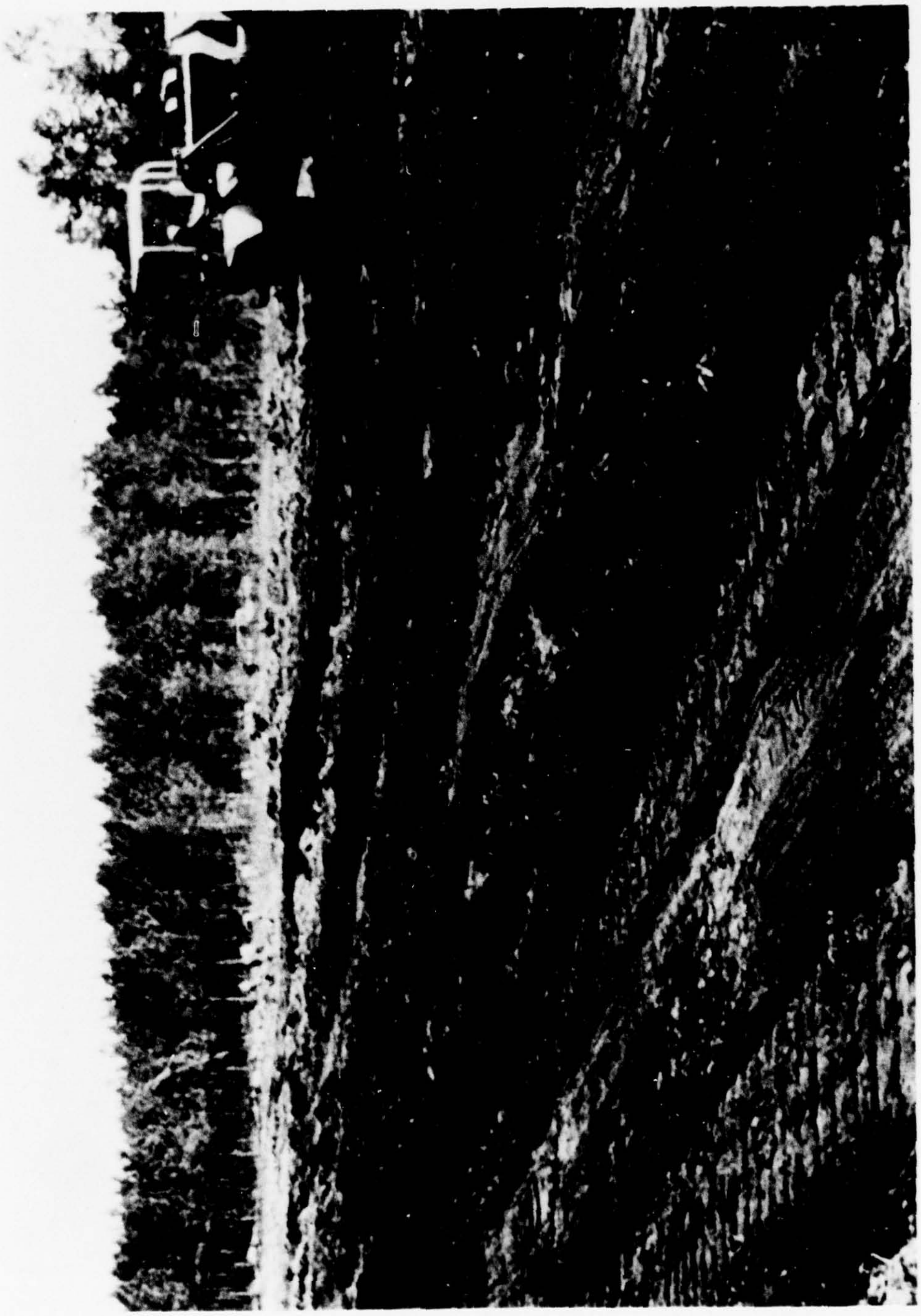
Armored Personnel Carrier (APC) configured for range clearance operation.

Surface/Subsurface Clearance Vehicle (SSCV) in operation sorting debris from soil.





Remote controls attached to a bulldozer.



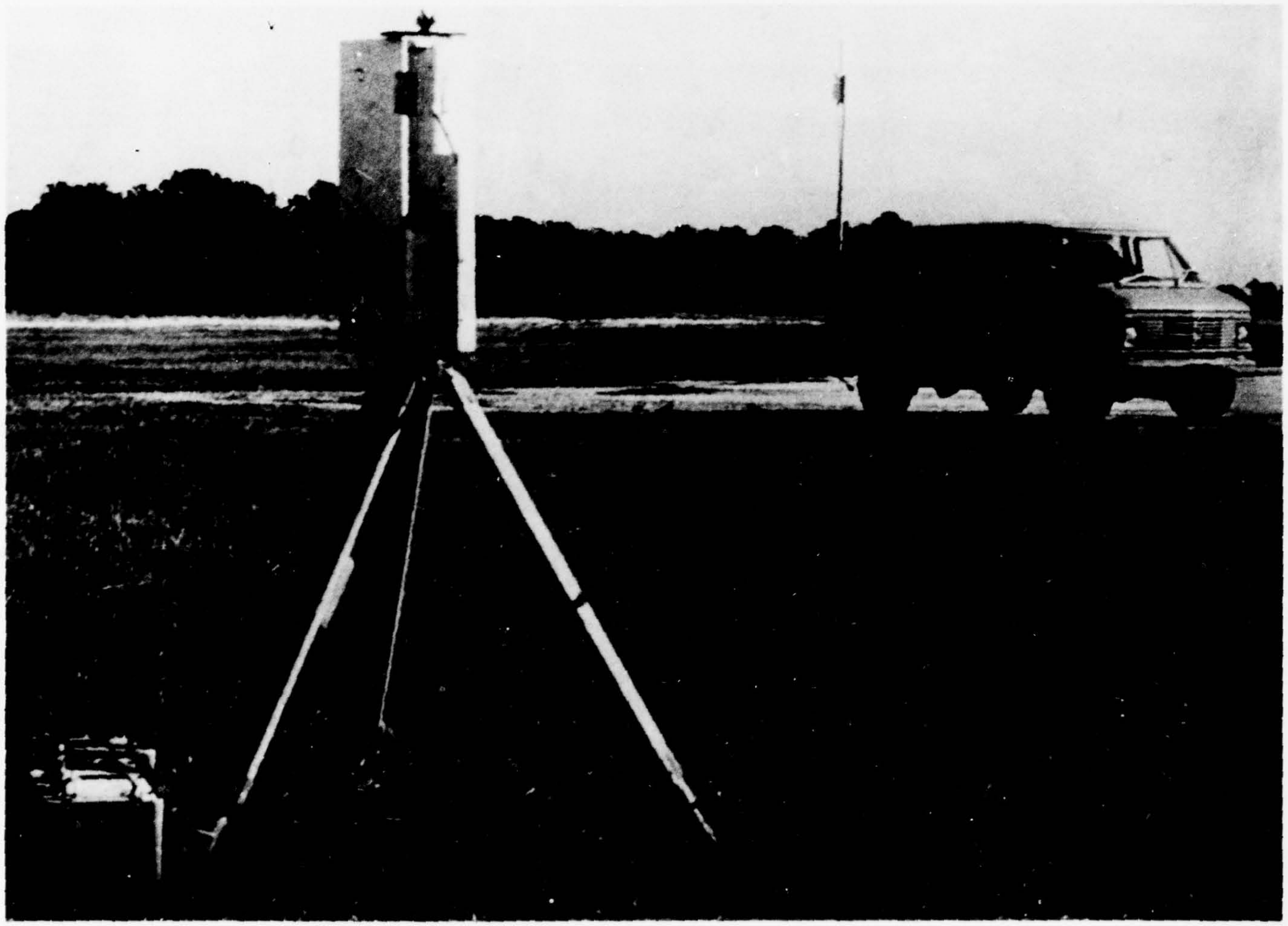
Clearing Putnam Target Range
with construction equipment.

Ordnance debris removed from
Putnam Target Range.

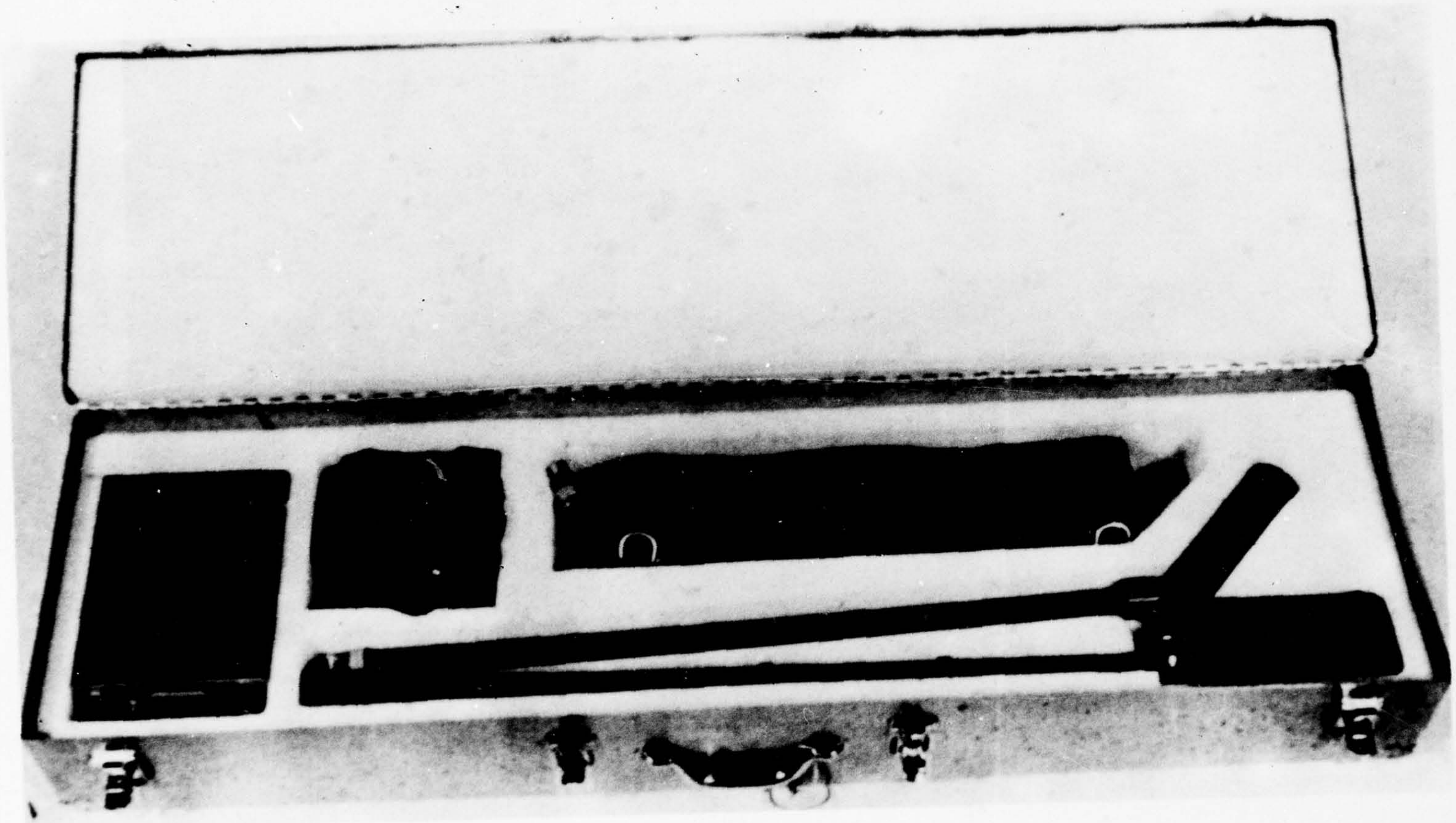
Prototype Surface/Subsurface
Clearance Vehicle (SSCV)

Total Containment Vehicle (TCV) capable of containing forty (40) pounds of explosive.

Radio frequency positioning system being used to guide search vehicle in an ordnance search on land.



Ferrous Ordnance Locator assembly including sensor, power source, and visual display unit.



CLAIMS AGAINST THE ARMY BY MEMBERS OF THE PUBLIC BASED ON EXPLOSIONS OF ORDNANCE USED IN TRAINING ACTIVITIES

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The purpose of this paper is to assist in an examination of the problems created by the polluting of military ranges and training areas by military ordnance, particularly duds. Special emphasis is made concerning the framework of the law and the payment of claims thereunder. Consideration is given to the value of such claims and the costs of payment.

Prior to WWII, the only means of compensation for injuries to or death of members of the public resulting from explosions, accidental or otherwise, of ordnance used in training activities was by private relief bills enacted by Congress. The United States had not waived sovereign immunity and the courts had no jurisdiction. The pressure of the large number of private relief bills resulting from a wide variety of governmental activities including the type under discussion resulted in active consideration of a general waiver of immunity as far back as the early 1920's.

A limited waiver of sovereign immunity occurred in 1942 when the Military Claims Act (MCA) (10 U.S.C. 2733) was enacted retroactive to the beginning of the War. Its announced purpose was to create public goodwill and was in general interest of the war effort. It is solely an administrative remedy and has no provision for judicial relief. It includes only a requirement that the injury be caused by the Armed Services. However, that has always been interpreted to require a negligent act or omission. In addition, claims arising from noncombat activities are payable provided the injured party's negligence

* The opinion expressed herein is the personal opinion of the author and not necessarily that of the U.S. Army Claims Service or the Department of the Army.

is not the primary cause of his own injury. The type of claim under discussion has always been considered as arising from noncombat activities. Thus the legal basis for paying almost any type of claim resulting from ordnance explosions has existed since the beginning of WWII. However, the cost resulting from such a wide basis of liability has never been a factor in determining the extent of the efforts to clear ranges and lands. This paper is the first such report to attempt to correlate the two.

The MCA and its noncombat remedy is still in effect and is worldwide in application. The noncombat activity provision is tantamount to a strict liability requirement. For example, it renders a child's injuries fully compensable even in absence of U.S. negligence if the child is legally incapable of contributory negligence. Whether intervening cause is defense is resolved on an individual case basis.

After consideration for about 25 years, Congress enacted the Federal Tort Claims Act (FTCA) (28 U.S.C. 2671-2680) effective in 1947. This is a general waiver of immunity and renders the United States liable in court to the same extent as a private person in accordance with state law applicable at the place the negligent act or omission occurred e.g. failure to follow state law and standards re safeguarding ordnance can render the United States liable under FTCA even though the United States is not required to follow such standards. FTCA is applicable only in the United States and its territories (i.e. other than foreign countries) and replaces all other negligence remedies such as the above MCA where FTCA applies. It does not supersede the noncombat provisions of

the MCA. Thus, even though the Army may successfully defend a case under FTCA on the basis that the injury did not result from negligence by the United States, a claim may nonetheless be payable under the MCA noncombat provision absent claimant's negligence. This is of course of prime consideration in cases which involve explosions emanating from ordnance utilized in training activities e.g., a person invited onto a military training area inadvertently explodes a piece of ordnance through no fault of his own or a stolen piece of ordnance explodes off-post injuring an innocent bystander. Nevertheless the MCA noncombat provision has not always been liberally interpreted. The attitude towards payment of noncombat activity cases has been liberalized as the courts have gradually expanded on the types of negligence necessary to render a case payable under the FTCA. Depending on numerous other factors it is generally better not to litigate solely as to whether there is any U.S. negligence and lose, thus paying perhaps more than full value after such loss.

The MCA does not have a limit on the amount which can be paid but in cases in which the amount to be paid exceeds a stated dollar value, a deficiency appropriation is required after approval by the Secretary of the Service. Currently it is for amounts over $25,000.00.

The FTCA on the other hand until 1967 required that, if the amount demanded exceeded a certain dollar amount, suit in a Federal court must be brought rather a claim against the Agency. At first suit was required for cases over $1,000.00. Later it was $2,500.00. Since most attorneys were and still are not familiar with the MCA and demands in explosive claims have always been grossly inflated, suits were usually brought under the FTCA, rather than as

administrative claims filed under the MCA because of the noncombat provision. This despite the fact that an attorney's fee under MCA is limited only by local procedure and usually ranges from 33-50% whereas under FTCA it is limited by the statute to 20-25%.

There was apparently little effort on the part of the Army claims authorities to inform claimants of the above, probably because in the early years of FTCA the Army usually won the suit. Thus, if suit were filed and lost under FTCA, the claimant was not informed that this case could be considered under MCA if the filing deadline could still be met. The suit was considered to be the end of the matter. The requirements to prove the Army's negligence were strictly construed under FTCA and a difficult burden for the claimant to meet. A study of the early cases clearly indicate this. However, by the late 1960's, the requirements shifted away from the claimants and his burden into what has now become the United States and its burden.

Thus the clearing of Camp Gruber, Oklahoma and its 65,000 acres was ruled in 1952 to be adequate by the 10th Circuit Court even though a booby trap left behind when the land was returned for civilian use injured by a minor living near the boundary in 1949 (Ford v. United States, 200 F.2d 272 (10th Cir. 1952)). By 1969, however, a District Court in Texas ruled that the clearing of Camp Barkley and its 23,000 acres to be grossly inadequate when a 37mm shell found by ranchers using the land exploded killing one adult and one minor and severely injured another adult and another minor when they were playing with the round in 1964 (Hernandez v. United States, 313 F. Supp. 349 (N.D. Tex. 1969)). The same type of formation of large numbers of troops following the same type of plan was used at Camp Gruber as at Camp Barkley. In 1972, an explosion

occurred of a 37mm warhead which seriously injured an 8-year-old boy who had purchased it at school for 22 cents from a 10-year-old boy who brought it in for a "show and tell" from the farm of his WWII vet father who was farming a portion of Camp White after it was turned over for public use. The case was settled by Department of Justice without a fight despite the potential of proving intervening cause against the farmer, the landowner, the local police, and the school, as well as the parents none of whom paid one cent.

In 1973, USARCS settled a claim for injuries to a six-year-old boy from an explosion of a 20 lb bomb removed from Camp Issequenna after its return to Clemson University to the home of the local sheriff where it hung on the garage for over 20 years being used for target practice. The range was cleared under contract but the contractor was deceased and had posted no collateral or insurance.

Stolen duds imposed no duty on the US in the older cases. In 1958 the Seventh Circuit ruled in favor of the United States in a case of an explosion of composition C-3 which killed an 8-year-old boy walking by in 1953 after the material was stolen by a soldier at Fort Belvoir (Voytas v. United States, 256 F.2d 786 (7th Cir. 1958)). There was a similar ruling by the 10th Circuit in an explosion of a bazooka dud stolen by a contractor employee baling hay at Fort Riley who took the dud 90 miles to his home where it killed three of his children and injured the other five in 1947 (Schmidt v. United States, 179 F.2d 724 (10th Cir. 1950)). However, the later cases are different. Thus in 1965 the 5th Circuit ruled the US liable for injuries to a 13-year-old male babysitter caused by an M-80 firecracker he ignited in Columbus, Georgia one

year after it was brought home allegedly by mistake by a training NCO who had long departed for Vietnam. The round was given to the boy by the Sergeant's wife just before the explosion (Williams v. United States, 352 F.2d 477 (5th Cir. 1965)). The case was remanded three times before the Circuit Court could get the District Court to pay it. The problem was finding the training NCO's negligence to be within the scope of his employment, a requirement under the law.

The trend of the law is clearly brought out in a ruling by a Federal court in North Carolina in 1970 in which an 8-year-old boy was compensated for injuries resulting from the explosion of a pyrotechnic device used to simulate aerial bombing after it was found by the boy and handed to him by his uncle in a Navy impact area. The excuse was all the neighbors had them on their lawn and the Navy encouraged it. (Duvall v. United States, 312 F. Supp. 625 (E.D.N.C. 1970)).

If it can be shown that the exploding dud was military in origin and it can be traced to a military range or training area, the FTCA in its present state would probably require that the injured party be compensated unless his negligence was the greater cause of the injury. However, even this is not a defense in jurisdictions which have adopted "pure" comparative negligence e.g., New York, California, Mississippi, Alaska, as there the claimant may be compensated for the percentage of his injuries attributable to US negligence, e.g. 10%, 20%, or whatever. The above rules are not certain as the case law is not certain or sure but provide a superficial overview. In fact a federal court decision can be found with just about any holding but most of the cases are older

cases. As stated above the few recent holdings are against the United States.

However, as broad as it may have become the FTCA requirement is still not as broad as the MCA.

Why claimant's attorney insist on using the Federal Tort Claims Act is even more difficult to understand in view of the fact that in 1967 the FTCA was amended to mandate that all claims must be filed with the agency, i.e., administratively, rather than directly in court prior to being permitted to go to suit. Thus a case is automatically reviewed by the USARCS under both FTCA and MCA when it is received. It is rare, however, that a disputed case can be disposed of under MCA without suit being filed under FTCA and sometimes a trial, although the latter is becoming very rare as the U.S. Attorney must nearly always be pressured to defend this type of case except where the negligence of the injured party is gross.

A suit under FTCA against the United States is decided by a judge alone and only rarely does he convene a jury to advise him. As to damages, punitive damages are not permitted. Thus the potential of an MCA award is the same as FTCA and as indicated above the fee potential much higher.

Another difficult-to-understand aspect is the apparent resentment of post level personnel responsible for firing activities and the like to the payment of such claims. This attitude probably is related to an attitude of disdain which prevails generally among scientific or technical personnel towards people who insist on mistreating manufactured objects and procedural safeguards relating to such objects with disregard for their own safety. The effect of this attitude is

to make it difficult to get cooperation in the investigation of these matters and a desire to coverup what will become known in court. Attempts are made to deny USARCS access to facts which are generally known locally and which in certain cases if made accessible would greatly facilitate settlement of these cases for smaller amounts. The fact is that the only "dead" claim is a paid claim. Witness current efforts re the drug test program and the nuclear test program.

Financially the burden imposed by the expansive interpretation of the law on the Army has not been great. Certainly greater efforts to avoid explosive incidents would impose much greater costs. However, in the investigation of these cases USARCS is frequently at a loss to understand certain activities at post level concerning the safeguarding and disposal of explosives. Duds are dumped in unguarded trash heaps, duds are left to lie by the hundreds in unmarked and unfenced impact areas readily accessible to dependants' housing, hunters, fishers, picnicers, horseback riders, hikers and joggers. In fact recreational usage of range areas is encouraged. Fish and wildlife personnel stock such areas. The usual protection relied on is by marking the impact area with signs reading "impact area" or "U.S. Property" or "no trespassing". The signs are frequently old, falling down and not near any recognizable route of travel. To add to the confusion the Daily Bulletin informs that the areas are off limits. Exactly which area is rarely defined. The perimeters are rarely marked. Fences are not present or broken down.

In a 40mm HE grenade explosion thrown by a 17-year-old (injuring himself and four other boys 13-15, killing one and seriously injuring three), the following was revealed by investigation.

"The last range sweep of Range 7 by EOD personnel was on 5 April 1972 when 300 40mm HE grenades were located and destroyed. A partial lane sweep of

Range 7 was conducted by EOD personnel on 12 October 1972 for placement of targets, 51 dud 40mm grenades were destroyed. The last time EOD personnel were on Range 7 prior to the above incident [19 Feb 1973] was 24 October 1972 when 31 40mm grenades were found. At that time EOD personnel recommended that a complete range sweep be performed as soon as possible. The range was eventually cleared in March 1973. On that occasion 1,376 40mm grenades, both HE and practice, were cleared."

The range was unguarded and unfenced yet near the boundary of the post.

The only signs were "Danger" signs and these not on the road used by the boys.

Query - Why use HE and not practice rounds? Why both on a range so located? The post is Fort Dix and the adjacent off post area is heavily populated. All the "kids" went on the range without challenge easily avoiding infrequent MP patrols. Without fences, guards, appropriate warning signs and inaccessibility to all but those participating in training, this type of case is indefensible.

On 5 April 1974 an explosion of a 40mm HE dud dropped in a road running by the range by an 8-year-old seriously maiming himself and killing his 10-year-old brother and 10-year-old neighbor, following tests by the Naval Ordnance Center of rebuilt High Velocity Automatic Machine Guns firing 3,000-8,000 rounds at each testing less than a mile from the on-post home of the boys. The investigation states that the Navy test fired on January 10, 11, 16, 23, 25, 29 and 31 and on February 2, 5, and 8. The Fort Knox Range Control records reflect several different and additional dates including 19 February. Both the Navy and Range Control agreed the records each kept were inaccurate and not coordinated. EOD records show 82 duds destroyed on 1 April. On 9 April, 64 more duds were destroyed. In

the following month 386 more. No firing at all took place in April.

On 5 April, the post newspaper warned of duds. A warning display was at the local school prior to the explosion. The father was a training NCO. Both parents had been horseback riding on the ranges with a group led by a "Colonel". The investigation states:

> ***"the uses of the ranges on occasion in sanctioned recreational activities e.g., hunting and horseback riding, to include not only those stationed at Fort Knox but members of the public generally created a false sense of security."
>
> Deer hunting and other recreational use was governed by a recreational control map designating 100 acres total of numerous small areas impossible to orient on the ground from the map. There are no fences or barriers. The reason the Navy used HE rather than practicewas that there was a surplus of HE.

In another Fort Knox case a public picnic area was used for night training. A booby trap left behind seriously injured a 13-year-old off post female vistor's hand. The map utilized by USARCS to find the area mistakenly identified an uncleared swamp used for aerial bombing since WWII as the picnic area.

On 22 February 1970, a 15-year-old boy lost sight in one eye and received broken legs and arms and other injuries, when a 16-year-old threw a 40mm HE grenade at the 15-year-old and also injured himself just off post at Fort Carson. Both boys had gotten a sackful of duds at an unfenced and unguarded range just off the interstate Highway. The usual "danger" and no "trespassing" signs were present. There may have been a "dud" sign but this could not be shown and was

probably put up later. Ordnance obtained from the ranges were common items of sale in the nearby off-post school. The local range SOP required that the unit remain until EOD personnel arrived to destroy all duds marked by the unit. The range had been cleared last on 14 February and had been used several times since.

In yet another Fort Knox case a trainee obtained a 90mm HE dud when he and several others went down the recoiless rifle range with the CO to look for "door stops". His CO consented as the round looked "different". He went on pre-embarkation leave to his buddy's home in Salt Lake City taking the 90mm HE dud and a dummy 105mm projectile on a United flight. One year later the dud exploded after being thrown into the weeds when his buddy's parents moved. Five children ages 3-13 were killed. A 10-year-old boy had found it.

These are not designed to be horror stories but to illustrate a usual point often discovered in USARCS cases that it that safety is often an expression of economics and as a result has taken a rear seat. However, the answers to many of the discrepancies is not always economic in nature. Were procedures and local SOPs followed the cases would present less exposure at trial. In the cases cited above most of the facts were not known to the plaintiff's attorney. If they had been, the cases could not have been settled but would have been tried in an effort to gain an inflated award, a backhanded method of achieving punitive damages not permitted against the United States. The total settlement costs were $541,000.00 for all concerned in the above five cases, that is eight killed and eight injured, although the two grenade throwers were not compensated and required to agree not to claim in lieu of an indemnity action by the United States not being brought against them.

Since the administrative filing requirement under FTCA in 1967 there have been claims filed in 58 incidents. Many more incidents have occurred and not resulted in claims. None of these are surveyed here as the source of information is from claims file, 55 of which were located and used in this survey. The three lost files involve minor cases of small amounts.

In the twelve years time period, the 55 cases involved 95 injured or killed of which 15 died, 33 were seriously injured and 26 received injuries mainly to one or both hands e.g., from booby traps, simulators or the like.

A total of $2,200,000.00 has been paid out in settlements either administratively or pre-trial and one judgment. Of the unsettled cases pending and in which U.S. liability is probable, the estimated value is $3,125,000.00.

Up to and including 1976, $1,131,863.00 was paid and no litigation is pending. In cases since 1976, $1.1 million has already been paid and a potential of 3.1 million exists. 1978 has brought out some large cases which cannot be settled because of the exorbitant demands. The total amount claimed for all 12 years is $46,444,291.43, while the paid and potential liability equals 5.3 million. The figure should be compared with an estimated cost of insurance for the activity if such insurance could be obtained. The following cases recently went to suit as the demand was too high.

In one case, a 9-year-old son of an officer went to the unfenced grenade range less than a mile away from his home and brought back duds which were discovered and destroyed by the EOD. The boy received one hour's restriction and then retrieved a dud he had concealed in a tree. He exploded the dud in the face of a 10-year-old neighbor girl injuring both children. When USARCS

attempted to advise the post investigator, we were informed that it was post business and both sets of parents had said no claim would be filed. The investigation indicated proper procedures were followed and no dud problem existed. Our investigation indicated hundreds of duds still in place and not yet cleared - the same situation as had existed in 1970 in the same range during another case in which a 10-year-old was killed.

Claims were filed but only the boy's claim can be settled. The girl's parents want 3 million. Their attorney wants 1 million. The case is worth about $250,000.00. The injuries are almost identical to the Camp White case discussed previously.

In another case a 27-year-old Bible student (VN vet) stated he discovered a LAW just offpost in a field across from his home in Colorado Springs. As he was collecting aluminum scrap (he was a janitor working his way through Bible college), he struck the dud on concrete to obtain the tailfins. He said that he thought it was a flare like he had seen in VN. The case is worth no more than the other Fort Carson case discussed above although he is almost blind in both eyes rather than one as with the above case. However, our offer was refused even though the attorney recommended acceptance. His attorney also is suing the designer of the LAW and Lone Star as the assembler and on the theory that if the round had been properly designed and manufactured, a dud would not have been created.

Our series does not involve injuries to service members as they cannot recover under FTCA (by case law) or MCA (by the wording of the statute) and claims filed by them are not counted even though filing is fairly frequent despite the legal barrier.

On the 55 cases, 7 have been denied four of which have gone into suit. Three others have gone into suit because of inadequate offers e.g., the two cited above. Only two were litigated and have gone to judgment, one judgment against and one for the US. The one against involved a stolen booby trap placed on his girl friend's gate by a Fort Leonard Wood trainee which exploded injuring her mother's hand ($50,000.00 judgment). This case is unreported. The one for involved a grenade stolen by a Navy Chaplain's son from the Fort Campbell range which he gave to his teenage friend. When the claimant wouldn't name the friend, we denied the claim and won in court (Simpson v. United States, 454 F.2d 691 (6th Cir. 1972)).

The ordnance involved includes 24 simulators, 7 40mm HE grenades, 6 other types of grenades, 4 LAW (66mm HE), 3 105 HE artillery rounds, 11 miscellaneous e.g., blank cartridge, shotgun shell, cherry bombs. These explosives came from 39 active Army and NG posts, 2 inactive posts, 7 reserve and NG armories, 1 US cemetary, 3 from overseas, and 3 unknown. At least 10 major Army posts with training activities were not involved, for example Fort Meade where USARCS is located. A recent explosion at Fort Meade involved a dependent who was injured by a 40mm HE grenade dud. A typical article appeared in the post newspaper following the incident relating that there was danger on the ranges from firing actually going on due to the road network. No mention was made of duds as Stokes mortar dating back to WWI and their dangers. The articles states that signs were posted warning of the dangers. However, tracing the route followed by the injured party the only signs found were "no trespassing" and "US property". No claim has been filed.

The ages of the injured and killed are as follows:

5	under 5
18	6-10
39	11-15
12	16-20
10	21-30
11	over 30

18 of the explosions occurred on ranges, 26 occurred after ordnance was carried off range (9 by minors). The rest may have involved duds from ranges in some cases but this is not certain.

In 13 incidents the ordnance was ignited with knowledge it would probably go off, although perhaps not with nearly the force encountered. In 26 incidents the ordnance exploded while being deliberately tampered with but without knowledge it would explode. 13 cases were pure accidents in which the presence of the ordnance was probably unknown.

In only 5 cases was the claimant not represented by an attorney although this is not a requirement under either FTCA and MCA. In all 5 cases the claimant recovered without suit. Many cases particularly those of minors could be settled without an attorney if reported promptly to USARCS as required by AR 27-20. These reports are rarely made. In fact, investigative reports are released to claimants without obtaining USARCS consent as required by the same AR. Thus it is not infrequent that, when a claim is finally filed, the claimant's attorney has more information than USARCS.

One continuing problem is that of public relations. Quite often the USARCS is the first Army representative to appear to the survivors and this is long after the incident.

From USARCS vantage point since most cases involving minors are payable and those involving culpable adults have been successfully defended when filed, it is doubtful that a different trend could or should be established in view of

the noncombat activity provision of MCA. The amount paid would not be substantially effected as preventative measures would not substantially reduce the caseload in all likelihood.

What is the solution. There is little continuity at post level and no one designated with overall responsibility and control of the problem. Dissemination of responsibility is fragmented and neutralizes any real overall effort at control. It is unrealistic to think that this is primarily a problem of local command and control. The local commander has not the desire, the authority, the resources, the background information or the finances to deal with the problem. A major effort at the highest level is clearly necessary.

This paper is addressed to those most familiar with the deficiencies herein and many of whom are much more knowledgable certainly on the technical or procedural aspects of explosive disposal. Perhaps it should be addressed to those in greater need of the information. This attitude raises the question as to why USARCS hasn't done something about it. The obvious answer is that we haven't been asked. Moreover if we went about trying to correct situations that give rise to claims, we wouldn't have time to settle claims. Once we mentioned the "dud" problem to our annual IG inspector but lost interest when the inspector said we'd have to "prove our case" just to be considered for the IG's annual list of topics. We didn't feel it was our case and still don't. But we are glad to provide what information we can. Questions should be directed to GC Division, USARCS, OTJAG, Fort Meade, Maryland 20755. Autovon 923-7803/4/5 or 6 - AC 301, 677-7803/4/5/ or 6.

EFFECTS ON STRUCTURAL LOADINGS
OF
BLAST LEAKAGE INTO STRUCTURES

by
Kenneth Kaplan[1]

The title of the paper is broadly descriptive; the term "blast leakage" applies to the effect of any opening in a structure. Thus the subject matter could also be described as "changes of loadings on structures due to openings in them." Openings considered include doorways, window openings, and vents.

The work leading to the paper[2] was done in connection with accidental explosions; therefore the first part of the paper will be a brief departure from the basic subject to express some cautionary thoughts about such explosions, and especially about the term "TNT Equivalent" used in connection with them.

ACCIDENTAL EXPLOSIONS AND TNT EQUIVALENCY

There is rarely a single number that can be quoted to describe the TNT equivalency of any material--except for TNT itself. Even in ideal situations (i.e., identical geometries) both peak pressures and impulses from different explosives generally change with distance differently than they do with TNT. Not only must explosive material characteristics be considered, (e.g., density, detonation velocity) but also such things as charge

[1] Now affiliated with Management Science Associates, Mountain View, California.

[2] Sponsored by the U.S. Army Armament Research and Development Command, Dover, New Jersey, (formerly Picatinny Arsenal). Carried out at Scientific Service, Inc., Redwood City, CA. The final report title is "Accidental Explosions and Effects of Blast Leakage into Structures."

shape and, if more than one explosion can occur, simultaneity of detonation. Petes, using this same forum 8 years ago, cited a case in which a particular propellant in a cylindrical geometry had "TNT equivalent weights" based on a TNT hemisphere ranging from 2.3 (at 100 psi) to 1.3 (at 3 psi), a very large difference. Compared with a TNT cylinder the "TNT equivalent weights" ranged from 0.4 (at 100 psi) to 1.I (at 3 psi), an even larger difference, which actually <u>reverses</u> the trend of the equivalency values based on a hemispherical charge. At 3 psi, the equivalency value is much greater than that at 100 psi.

Figure 1 illustrates some possible effects of geometry differences, in this instance between relatively tall cylinders (L/D = 3.8 and 5.0) and relatively flat, or pancake-like, cylinders. Clearly the "TNT equivalency" depends on whether peak pressure or impulse is considered and also on distance from the charge.

And odd geometries <u>can</u> occur, especially in accidental explosions. I will cite two extreme examples just for emphasis,

1. the linear nature of the 1944 Port Chicago ship explosions affected pressure values over seven miles away.
2. In 1967, the vapor cloud from an isobutylene leak at Lake Charles, LA, covered 200,000 ft^2 and was 20 ft deep before it exploded.

LOADINGS ON CLOSED STRUCTURES

Design loadings on closed structures have been developed from consideration of the kinds of shock wave-structure interaction phenomena shown in Figure 2 taken from Bleakney's work at Princeton University, done about 30 years ago, but still some of the best illustrations of blast phenomena extant. Figure 2A shows both the shock wave reflected from the front face of the block, and the rarefaction wave from the top corner already

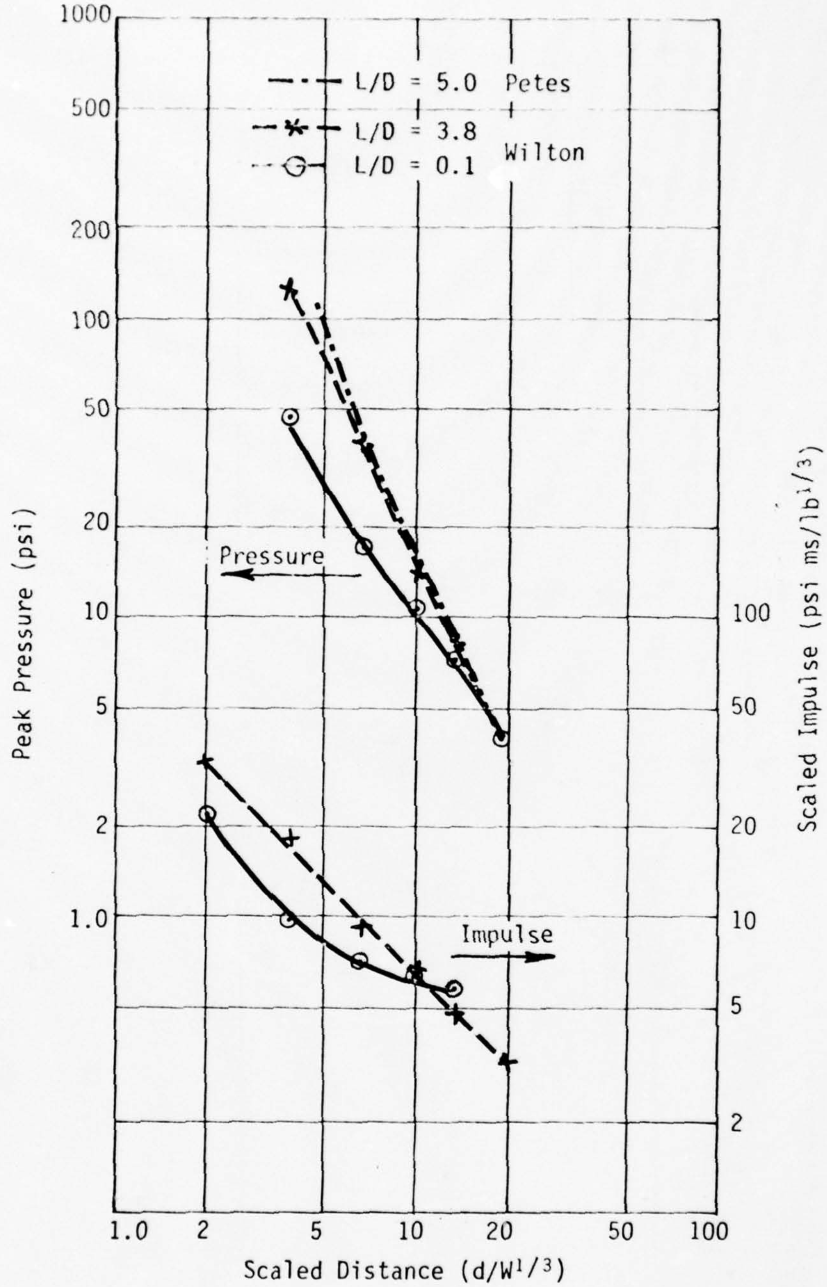
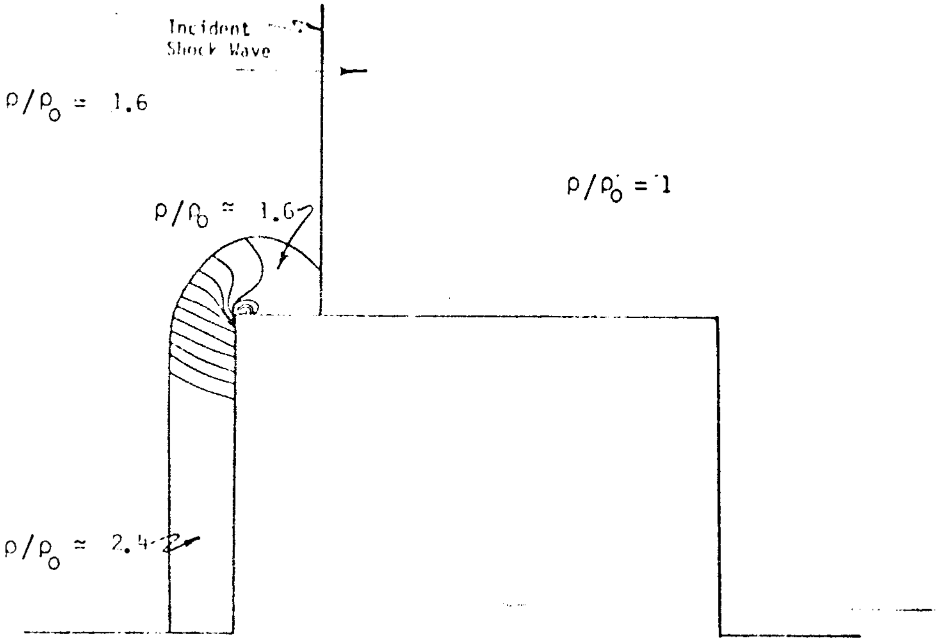
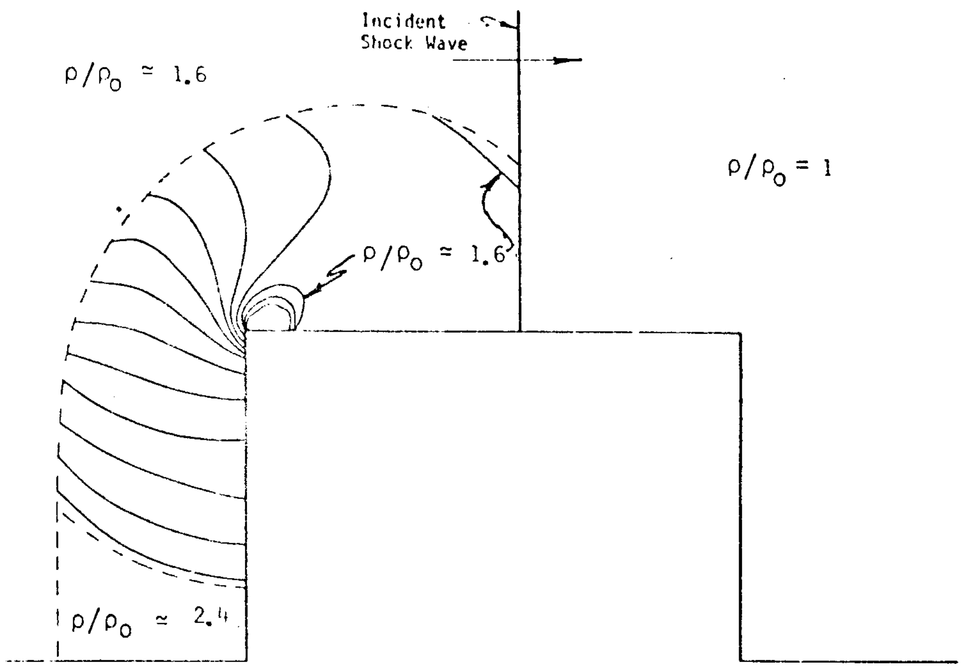


Fig. 1. Peak Pressure and Scaled Impulse vs Scaled Distance from Cylindrical Charges.
L = Axial Length of Cylinder
D = Diameter of Cylinder

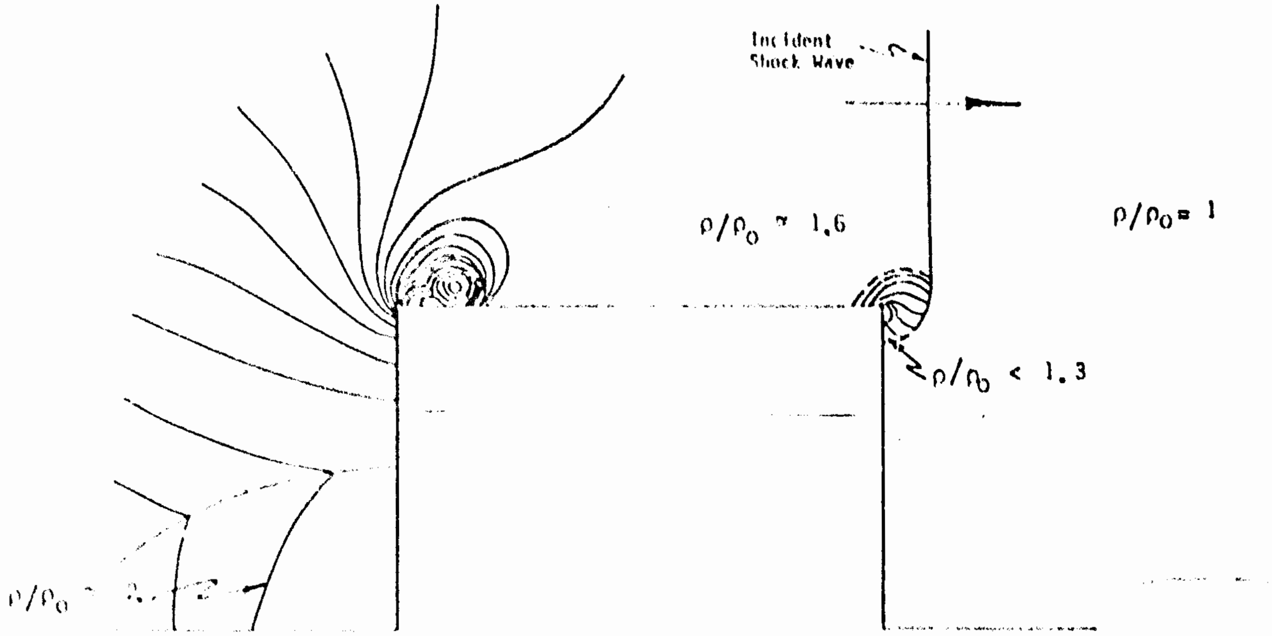


A. 15 μs After Striking Block

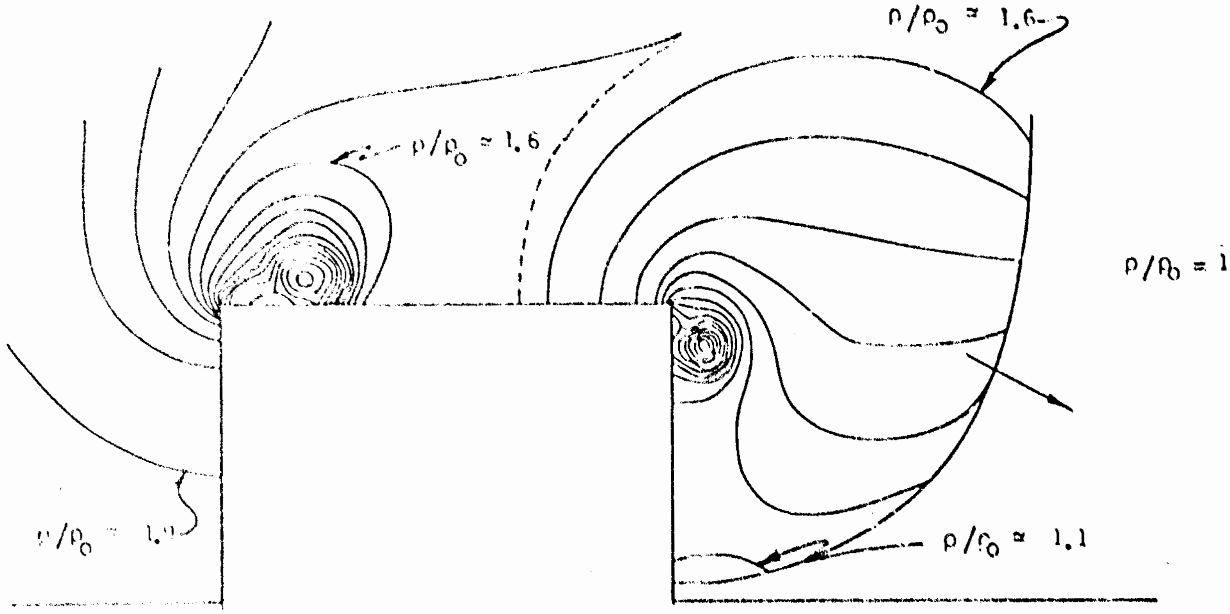


B. 45 μs After Striking Block

Fig. 2. Shock Wave Behavior at the Front Face of a Block. Isodensity Contours Behind the Shock are Shown. $\rho/\rho_0 = 1$ indicates ambient density; $\rho/\rho_0 = 1.6$ is density behind incident shock; $\rho/\rho_0 = 2.4$ is density behind reflected shock. Shock strength $\left[(P_{so} + P_0)/P_0\right] = 1.9$.



C. 90 μs After Striking Block



D. 149 μs After Striking Block

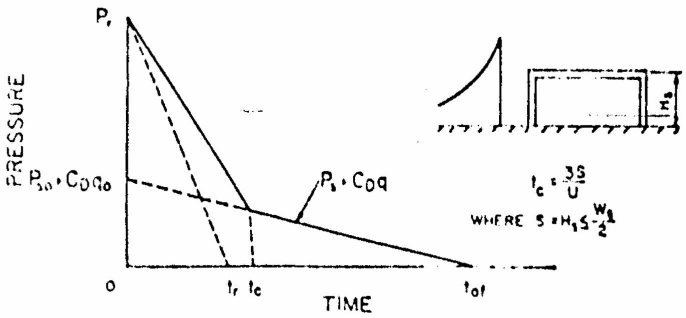
Fig. 2. Shock Wave Behavior at Both Front and Back Faces of a Block. Isodensity Contours are Shown. $\rho/\rho_0 = 1$ indicates ambient density; $\rho/\rho_0 = 1.6$ is density behind incident shock; $\rho/\rho_0 = 2.4$ is density behind reflected shock. Shock strength $[(P_{so} + P_o)/P_o = 1.9]$

proceeding down into the reflected wave and reducing its pressure. In Figure 2B the rarefaction wave is almost at the base of the block. In Figure 2C, the rarefaction wave at the front face has reflected from the ground. The incident wave has reached the back face of the block and is beginning to diffract onto that face. Pressures on the top of the block are essentially at incident values. Finally in Figure 2D additional reflections have taken place on the front face leading to a confused situation, but with loadings well below reflected values. On the back face, a slow pressure build-up has occurred, and the diffracted wave is just about to reflect from the ground surface.

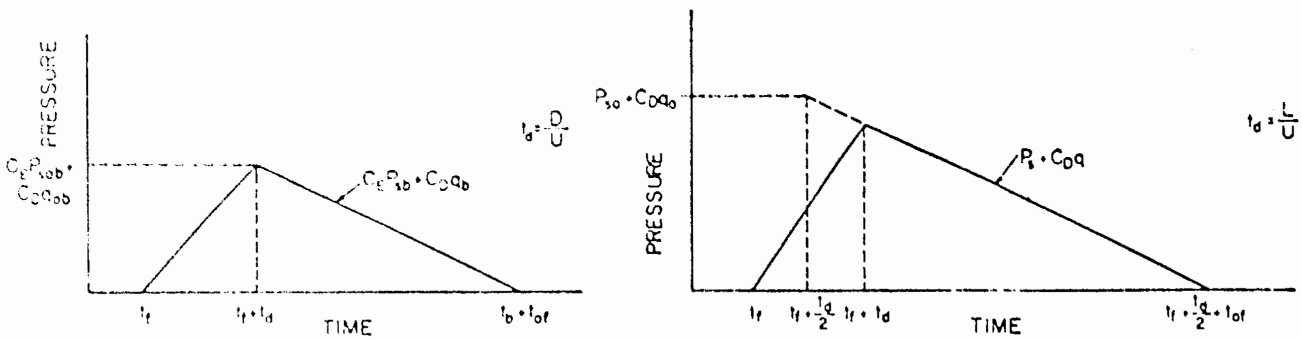
Generalized loading curves developed from these kinds of phenomena and are shown in Figure 3, front face loadings start at reflected values but quickly decrease to values near incident pressure. Roof, side wall, and back wall loadings gradually build up to near incident wave values.

It must be emphasized that these loading curves do not purport to follow what is actually happening on any face of a structure, which--as has been seen--can be extremely complex. They are intended, in essence, to summarize, to average out, all these complexities so that there is some apparently rational basis for designing structures. Many, many variations of these curves exist--some with double peaks, some with modified "clearing times" (i.e., the times for pressures to reach near incident values). Engineers called on to design structures to withstand blast waves with very long duration--a few seconds, for example as from nuclear weapons--tend to use the generalized loadings as they change with time. Others faced with designing structures to withstand short duration blast waves--a few ms or tens of ms long as from an explosion of conventional high explosives in reasonable (or even unreasonable) quantities--would tend to use the generalized curves to determine impulsive loads, without considering loading vs time variations.

The interest of this audience--and of the work done that led to this paper--is in the latter category, impulsive loads from

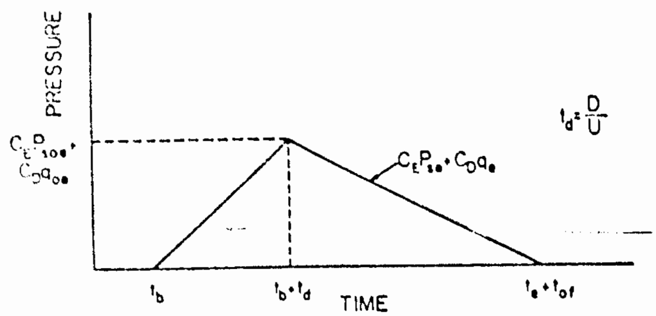


A. Front Face



1. Perpendicular 2. Parallel

B. Roof and Side Walls - Spans Perpendicular and Parallel to Shock Front



C. Back Wall

Fig. 3. Generalized Loading Patterns.

conventional high explosive sources.

EFFECTS OF OPENINGS

Exterior Loadings Only

Exterior loading changes are those that could occur where, for example, a doorway opens on a corridor instead of a room into which a blast wave could propagate. On every face of a structure, these change tend to decrease impulsive loadings. On the front face, the basic effect is to decrease clearing times; the openings essentially increase the area available for reducing pressures from their peak values. On the roof, sidewalls, and backwall, openings tend to reduce the maximum loadings attained.

Interior Loadings Only

Interior loadings caused by a shock wave outside an opening, that is, by the presence of higher pressure outside the opening than inside, can be of two types: those caused directly by the shock wave that passes through the opening; and--if the shock duration is long enough, or the opening is small enought(a vent, for example)--those caused by the very high speed jet of air that forms because of the difference between exterior and interior pressures.

Shock Wave Effects

Consider first, direct shock wave effects, and in particular those that occur along the axis of a room. Initially the shock wave along the axis doesn't "know" that an opening exists. Signals from the edges of the opening have not yet arrived at the axis. The signals eventually do arrive, and the wave eventually becomes curved. During this "intermediate" phase, a fair amount of experimental evidence--from both full-scale and small-scale structures--indicates that peak pressures tend to decay as the 3/2 power of distance.

Two of the experimental sources are shown in Figure 4 through 6. Figure 4 shows a full-scale structure that was subjected to blast from a nuclear weapon, and also a small model of the same structure tested in a shock tube. Figure 5 shows a large shock tunnel with a test area cross section $8\frac{1}{2}$ ft high and 12 ft wide, inside of which was built the 14.5 ft long room sketched in Figure 6.

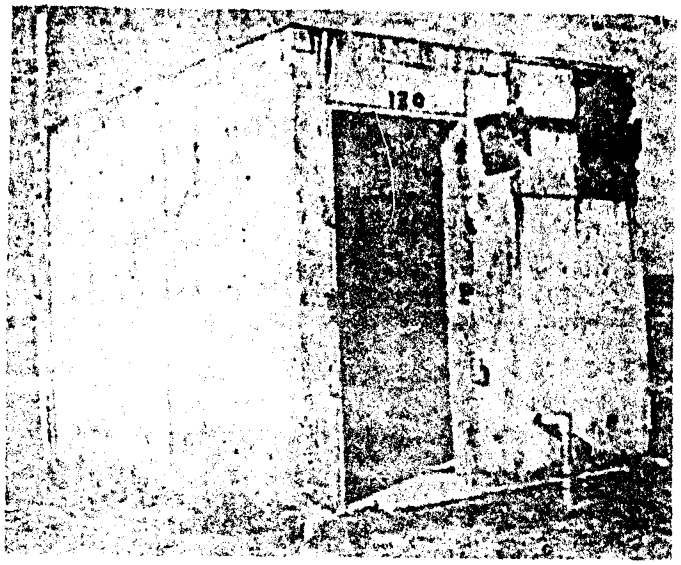
Data from these sources are shown in Figure 7, a plot of interior shock pressure relative to that at the opening as a function of distance from the opening relative to a measure of the size of the opening. The horizontal line represents the "stupid" shock wave phase; the lines furthest to the right, the 3/2 power relationship and the middle line, a transition phase in between the two.

As far as off-axis pressures are concerned, they can be expressed in terms of angle of departure from the axis in such a way that they modify the curves of Figure 7, with pressure decreasing as angle of departure increases. There is some shock tunnel confirmation of the effect. The final phase of shock wave behavior only occurs if the room behind an opening is very long. In that case, the wave tends to become plane again. Application of momentum conservation principles also allows the expression of relative pressure after the wave has become plane in terms of relative distance from the opening.

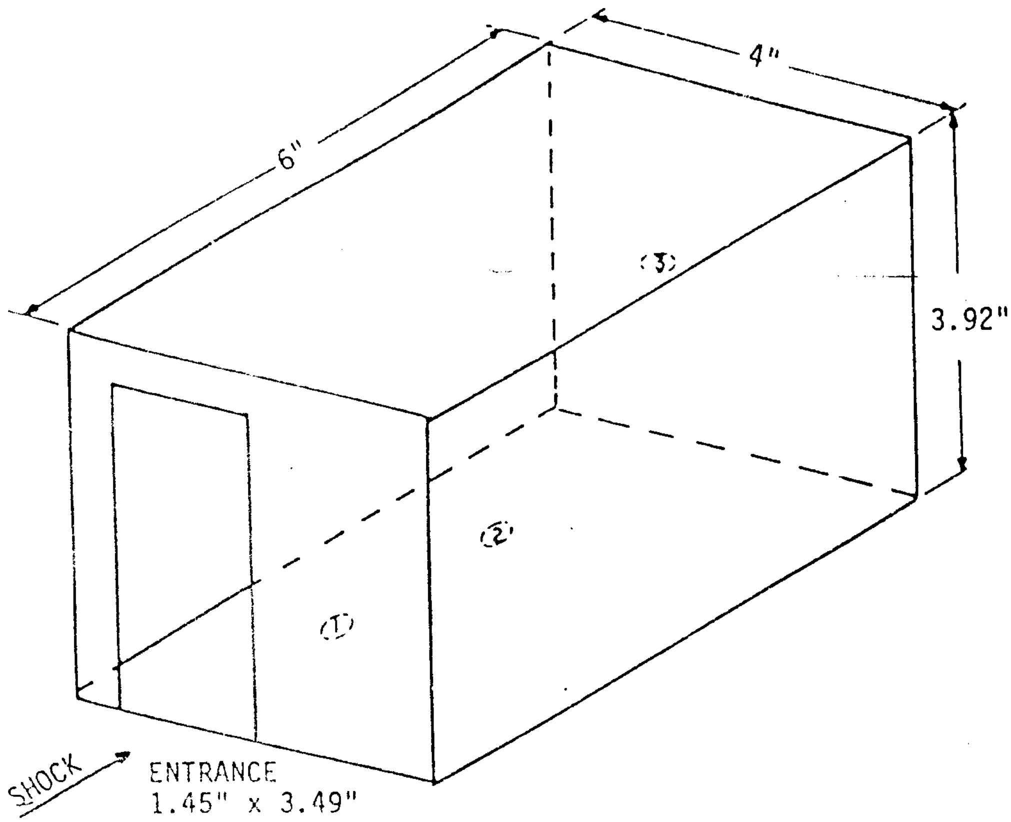
Figure 8 essentially summarizes all these shock wave effects.

Jet Flow Effects.

The general character of the jet that can form sometime after a shock wave strikes an opening is shown in Figure 9. First, there is a high velocity core with uniform flow across it; then after a transition section, a region in which velocities gradually change from zero at the edge of the jet to a maximum at its center. A very important fact to consider is that this jet does not spread out very much, unlike the shock wave.



A. Field Structure - Dimensions are 8 ft x 8 ft x 12 ft.
Doorway is 2.9 ft x 7 ft.



B. Model of Field Structure Tested in a Shock Tube.

Fig. 4. Structures Exposed to Blast Waves in the Field and in a Shock Tube.

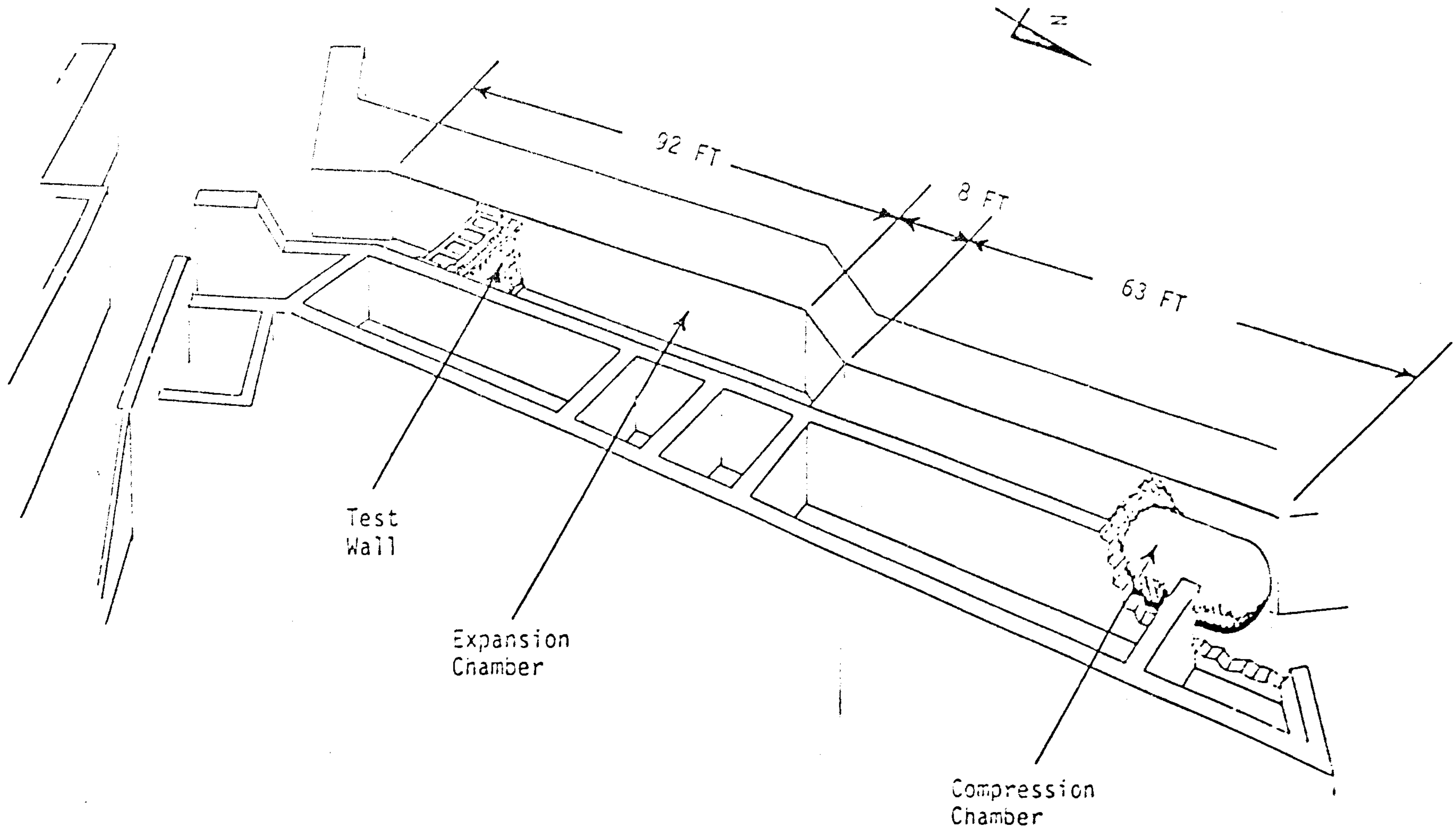
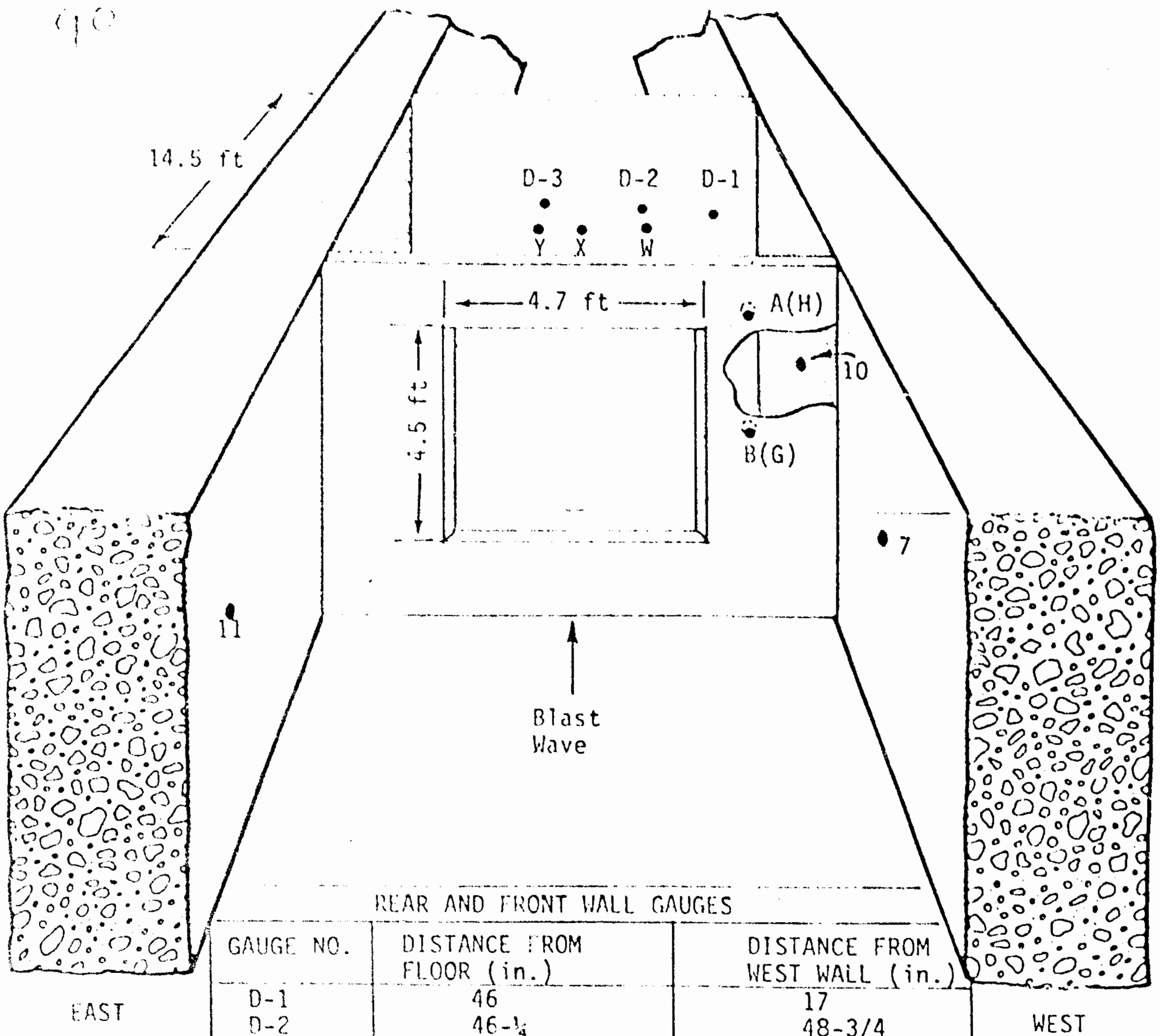


Fig. 5. Cutaway View of Shock Tunnel Showing Wall in Place.



REAR AND FRONT WALL GAUGES

GAUGE NO.	DISTANCE FROM FLOOR (in.)	DISTANCE FROM WEST WALL (in.)
D-1	46	17
D-2	46-¼	48-3/4
D-3	46-3/4	95-3/4
W	44	46-3/4
X	42-1/8	84-3/4
Y	42-¼	96-3/4
A(H)	83-½	30
B(G)	51	28-½

SIDE WALL GAUGES

GAUGE NO.	DISTANCE FROM FLOOR (in.)	DISTANCE FROM FRONT WALL (in.)
7	45	21
11	49	38
10 (in room)	49	67-1/8

Fig. 6. Room with a Window Test Configuration in the Shock Tunnel.

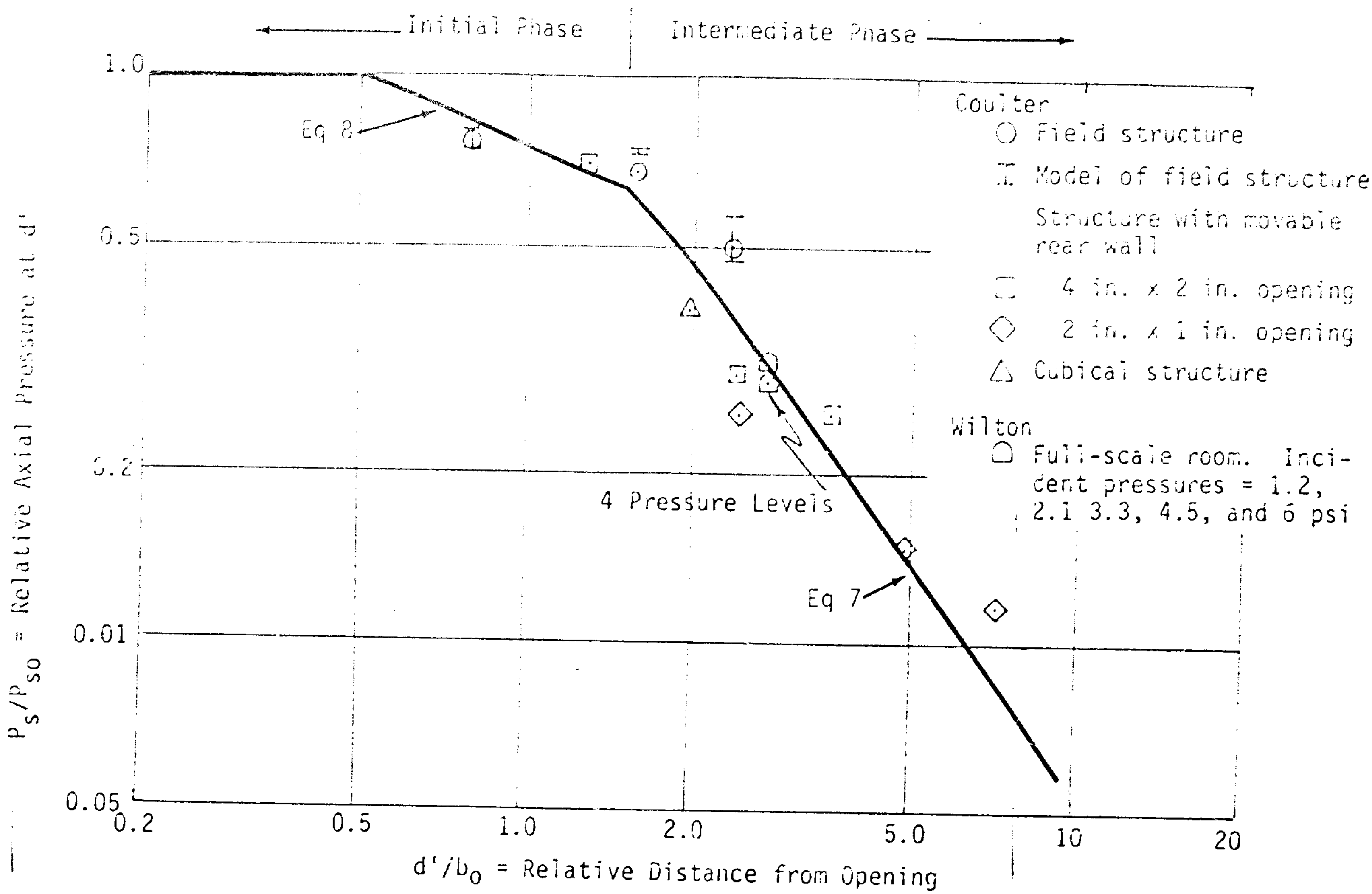


Fig. 7. Comparison of Predicted and Experimental Axial Shock Front Pressures — Initial and Intermediate Phases. Opening Width = b_o; Distance from Opening = d'; Pressure at Opening = P_{so}, Axial Pressure at d' = P_s.

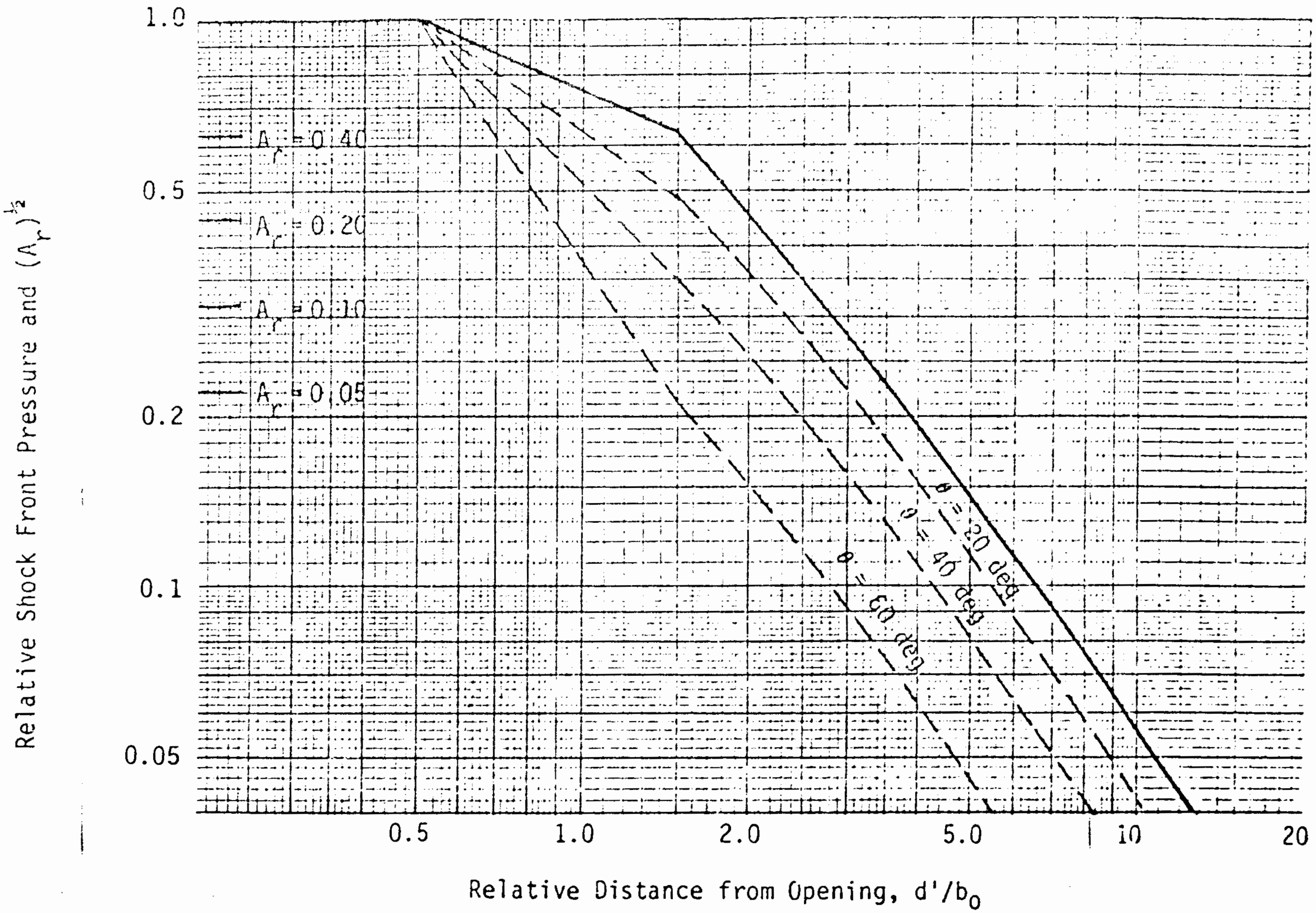
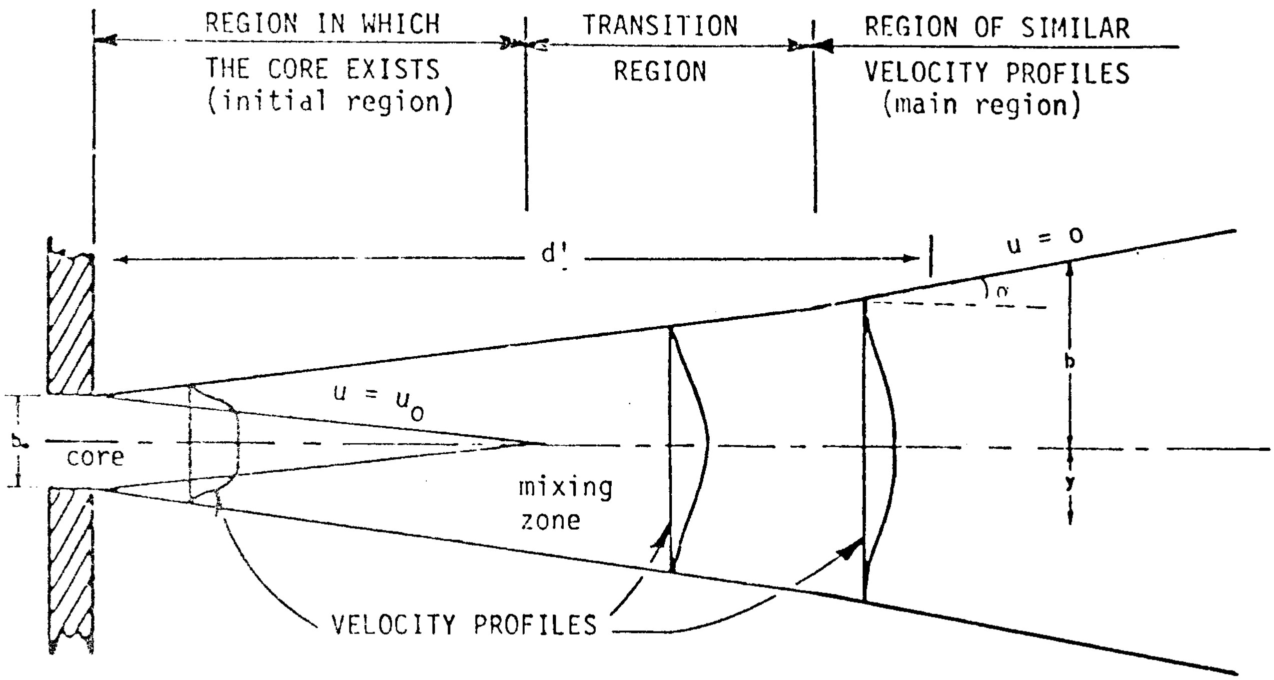


Fig. 8. Prediction Curve for Axial Shock Front Pressures (see instructions for use).



F 9. Jet Flow Characteristics

That velocities--and more important, dynamic pressures--in such a jet can be very high relative to values directly behind a shock front is shown in Figure 10.

I should emphasize that it takes a finite time for such a jet to form (a time that depends on the size of the opening) so that jet flow may not be a consideration in many situations involving high explosives.

Net Loadings.

The combination of the effects of both interior and exterior loadings can be significant indeed. For example, changes in loadings on a wall with a window derived from full-scale shock tunnel experiments are shown in Figure 11.

Examples Illustrating Effects of Openings.

The conclusions and techniques just described have been applied to a number of different situations to get some feeling for their possible importance. The first situation involved the structure shown in Figure 12A, located 340 ft from a 10,000 lb. charge, that is where peak incident pressure would be 4 psi and the blast wave duration 65 ms. The very large changes in impulsive design loadings from those on a closed structure are shown in Figure 12B, 12C, and 12D. On the front and side walls, initial impulses are reduced by more than a factor of two, and a second loading, due mainly to the shock wave reflecting from the backwall and returning to the front wall, causes the direction of loading to reverse. On the back surface the entire impulsive load is reversed from its direction with a closed structure.

In another situation, accelerations of objects inside a room due to core jet flow were calculated for a shock wave from a 7000 lb charge and a structure 240 ft away from the charge with a window opening. (peak overpressure, 5 psi; duration, 54 ms). In these circumstances, a crouching man could

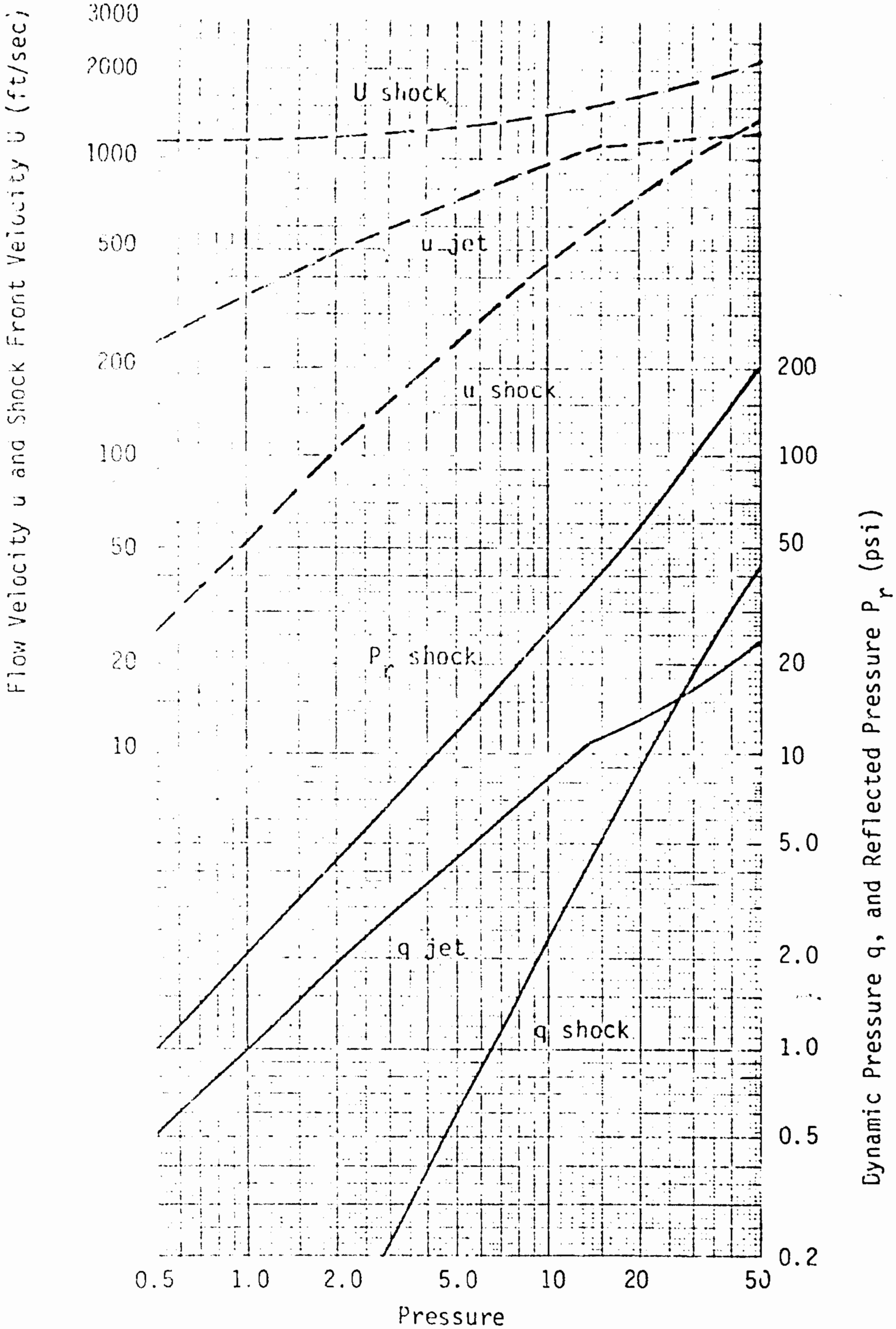


Fig. 10. Shock Wave and Jet Parameters: Dynamic Pressure q, Flow Velocity u, Shock Front Velocity U, Reflected Shock Pressure P_r.

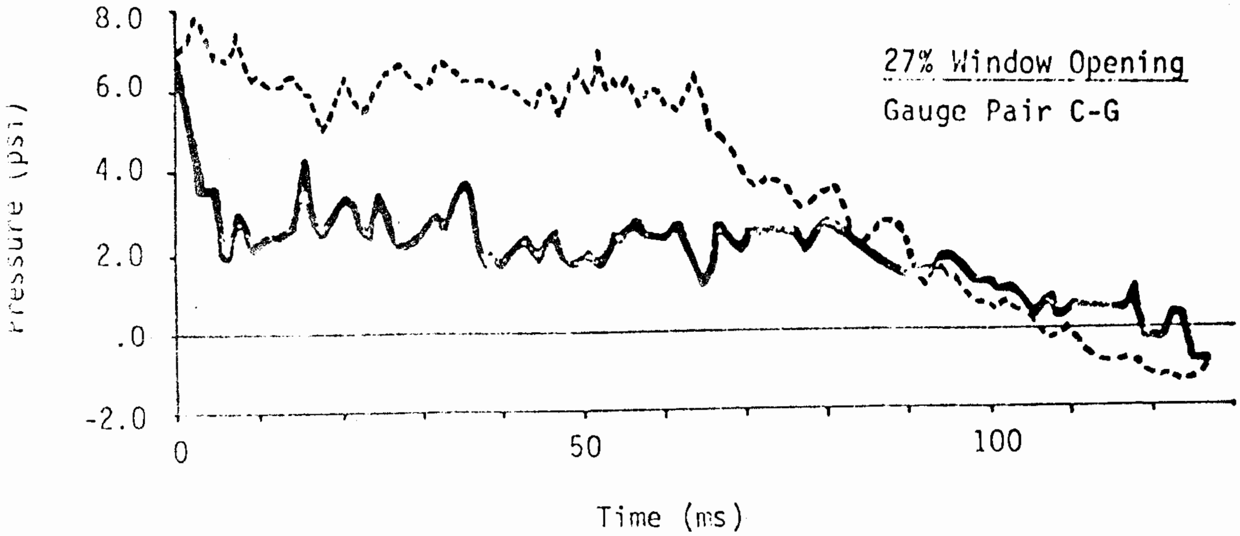


Fig. 11 A. Localized Net Pressure vs Time from Paired Gauges from Tests with Incident Pressures of 3.3 psi. Solid Curve is for a Wall with a Window, Dashed Curve is for a Solid Wall. For Gauge Locations see Fig. 6.

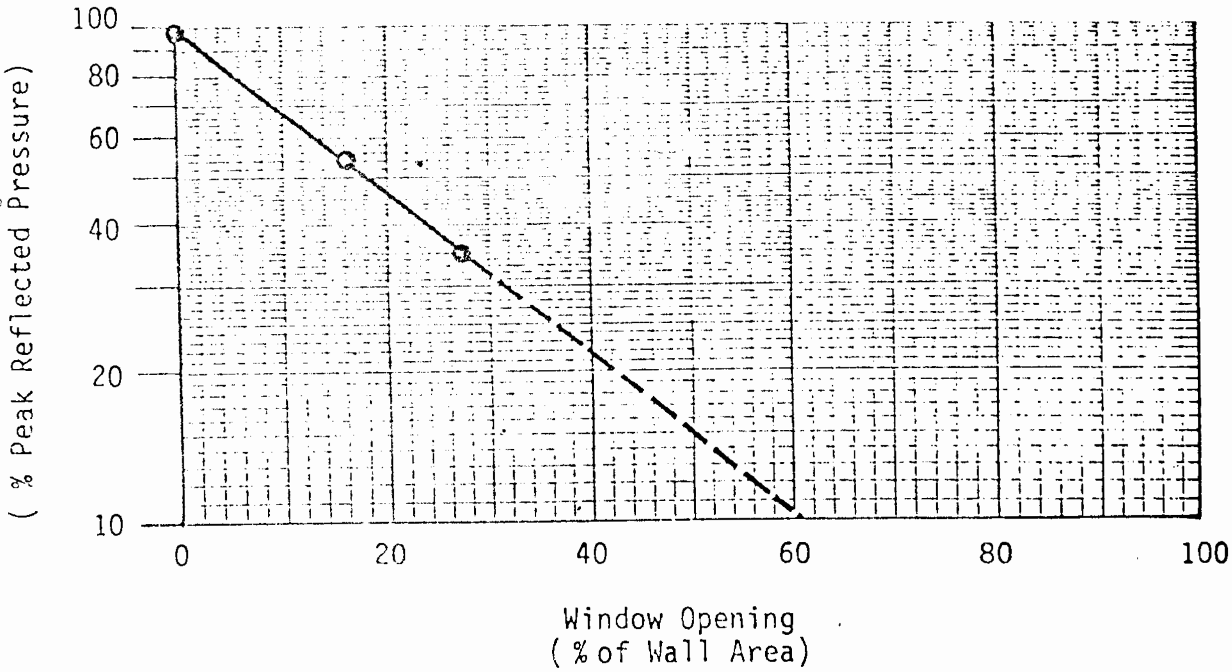


Fig. 11B. Net Loading on a Wall with a Window as a Function of Window Opening Area.

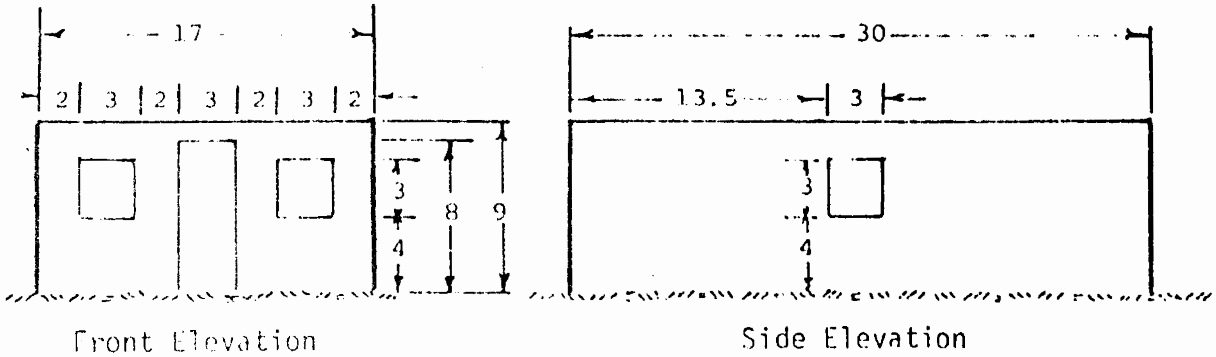


Fig. 12A. Structure Used in Example No. 1. All dimensions are in ft.

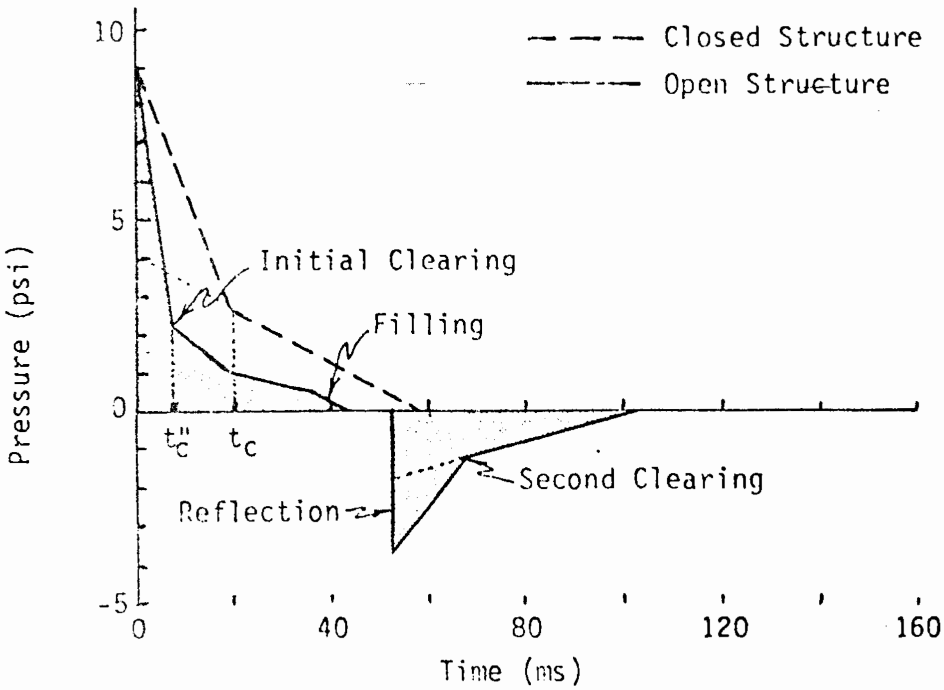


Fig. 12B. Front Wall: Net Loadings for Closed and Open Structure Shown in Fig. 12A.

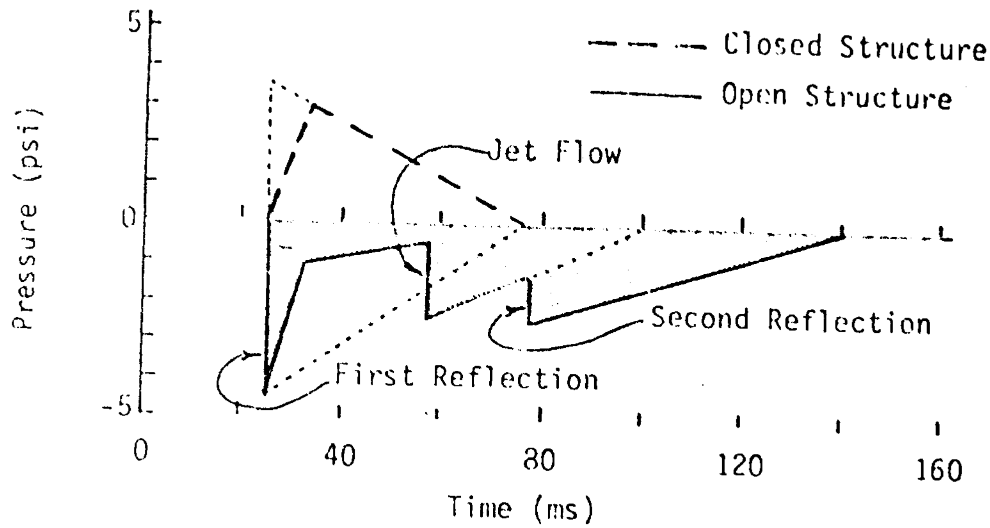


Fig. 12C. Rear Wall: Net Loadings for Closed and Open Structure Shown in Fig. 12A.

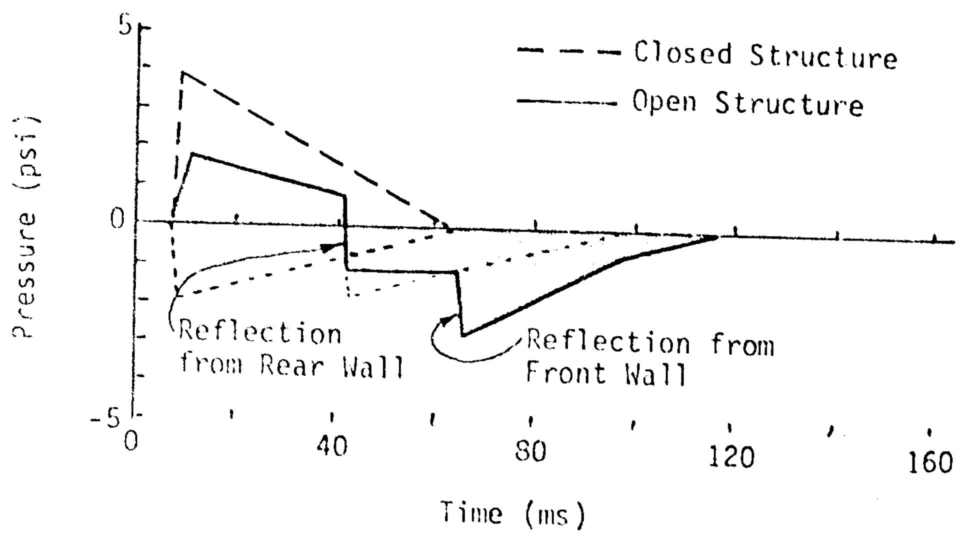


Fig. 12D. Side Wall: Net Loadings for Closed and Open Structure Shown in Fig. 12A.

attain a velocity of about 5 ft/sec; a small stone about 40 ft/sec; window glass, about 90 to 200 ft/sec.

The final example is for a structure designed to withstand very high pressures (50 psi) such as might be experienced by a control room near a test cell. From a 5000-lb charge, a duct, or cabinet, or any other flat surface three ft from an 8-$in.^2$ vent would experience a maximum force of more than a ton, and a total impulse of more than 12,000 lb ms. The loading would only last for about 8 ms, and would only be applied over a 16-$in.^2$ area of the surface.

SUMMARY

Openings in structures (e.g., doorways, window openings, vents) can substantially alter impulsive loadings used for design. If there is enough time for a jet to form, free-standing interior objects can attain significant velocities, and interior surfaces can experience large forces.

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RESULTS OF ANALYSIS OF

PRE-ENGINEERING BUILDING

BLAST TESTS

by

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ABSTRACT

This paper summarizes recent and on-going ARRADCOM tests for the development of design criteria and procedures for acceptor structures located in low to intermediate pressure ranges. Test procedures and results and design criteria are presented for pre-engineered buildings. The data presented supplements the data on acceptor structure design given in PTA report 4837 and ARRADCOM report ARLCD-CR-77008.

INTRODUCTION

The U. S. Army, under the direction of the Project Manager for Production Base Modernization and Expansion, is currently engaged in a multi-billion dollar program to modernize and expand its ammunition production capability. In support of this program, the Manufacturing Technology Division of the Large Caliber Weapons Systems Laboratory, ARRADCOM, with the assistance of Ammann & Whitney, Consulting Engineers, has, for the past several years, been engaged in a broad base program to improve explosive safety at these facilities. One segment of this program deals with the development of design criteria for explosion resistant protective structures.

Development of this design criteria has, in the past, been primarily concerned with structures located in the high pressure region close-in to an explosion. The basic document to evolve from this effort is the tri-service manual, TM5-1300, "Structures to Resist the Effects of Accidental Explosions," (Ref. 1). This manual contains comprehensive information on the principles of protective design, the calculation of blast loadings, dynamic analysis, and detailed procedures for designing reinforced concrete protective structures.

It is common practice in the explosives industry, for process buildings associated with the same line, to be separated by "intraline distances" which are meant to provide a high degree of protection against the propagation of explosions from building to building. Similarly, the minimum distance permitted between an inhabited building, not associated with the line in question, and an explosives location is the "inhabited building distance". These distances are published in the DARCOM Safety Manual (DRCR 385-100) and are based on the cubic root scaling of the explosive weight which defines areas of equal pressure. In all cases, however, the blast overpressures that an acceptor structure would see in the event of an explosion in the "building next door" would be greater than a conventional structure is designed to withstand and serious injury to personnel within them is likely. In this regard, explosive tests have been conducted to evaluate the blast capacity of pre-engineered buildings. The results of these tests, which are described in this paper,

have been used to verify and refine data contained in the ARRADCOM technical reports pertaining to the design of acceptor structures (Ref. 2 and 3).

In general, acceptor structures relate to buildings located in pressure ranges of 10 psi or less. These buildings contain personnel and/or valuable equipment which require protection against the blast and fragment output of an accidental detonation, particularly where hazardous operations are involved. The selection of the appropriate structural system and materials for acceptor structure design depends on overpressure level, degree of fragment hazard, explosive contents of the acceptor building, and normal operational functions. In some cases, existing structures are utilized in the modernization and expansion program and it is necessary that criteria be available for the evaluation of such structures, to determine their adequacy or modifications required to obtain the desired protection.

Steel buildings used for protective structures range from pre-engineered buildings for low overpressures (about 1 psi) to strengthened steel buildings for higher overpressures. One disadvantage of steel designs is that they provide little protection against fragment penetration, and may not be suitable for personnel protection where the contents or construction of the donor is such that a significant fragment hazard will be produced. On the other hand, when the structure may also be a donor structure, the designer must consider the effects of explosive contained within the building since in this case the use of structural steel (compared to masonry or concrete) minimizes the creation of fragments. The use of masonry, precast concrete and wood construction for acceptor structures is presently under study by ARRADCOM, and future testing of these materials is contemplated. For certain explosive facility designs, it may be cost effective to provide balanced protection against blast and fragments by combining the use of these materials; for example, masonry walls with steel frames and a wooden roof.

This paper describes a series of blast tests performed on pre-engineered buildings at Dugway Proving Ground in February, 1977. The recorded damage levels are evaluated and compared with those predicted by the methods and criteria given in References 2 and 3. Recommendations pertaining to the design of pre-engineered buildings for resisting blast loads are provided.

General

Standard pre-engineered buildings and their components are designed to resist dead, wind, seismic and other conventional live loads. However, they possess a significant inherent capability which, when utilized in the proper manner, will resist relatively large blast overpressures. This is particularly true when the ultimate dynamic strength is considered and inelastic deformations are permitted. Moreover, the blast resistant capacities of pre-engineered buildings can be further increased by decreasing the spacing of frames or other components and/or increasing the sizes of individual members, while still retaining standard pre-engineered building elements. Significant factors in the evaluation of the blast capacity of conventionally designed structures include the difference in the relative proportions of lateral and vertical design loads for conventional structures, and the differences in the dynamic response of secondary members relative to that of the frames. Quite often, it has been found that, for blast resistant designs, the frame selected for conventional loads is stronger than the secondary members and, therefore, modifications will be necessary. Although these modifications will usually require a cost increase, it will generally be small compared to the afforded increases in blast protection. Further, these added structural costs are usually more than offset by the cost savings achieved by building separation reduction.

Therefore, in order to verify those modifications which will produce increased capacity and to identify unknown shortcomings of pre-engineered buildings, a series of tests were recently performed at Dugway Proving Ground. These tests were sufficiently instrumented such that a quantitative evaluation, of the building response to blast pressures, could be made.

TRADE NAME CITATION

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Test Description

Blast tests of pre-engineered buildings were performed at Dugway Proving Ground during the weeks of January 31 and February 7, 1977. A total of six tests were performed with only minimal repairs required between tests. Each test utilized approximately 2,000 pounds of nitro carbo nitrate consisting of 94.5 percent by weight of ammonium nitrate and 5.5 percent by weight of No. 2 fuel oil. The explosive mixture was contained in cylindrical aluminum containers which were positioned on the ground and, depending upon the incident overpressure desired at the building, at various distances from the test structure. It was observed in several of the initial tests that, for a given selected scaled distance, the actual incident overpressure produced at the building was approximately 10 percent less than that anticipated, indicating that the explosive mixture had a TNT equivalency slightly less than one. Hence, to account for this difference, in the latter test, the distance that would ordinarily be used to predict a given incident overpressure was reduced, thereby producing good agreement between predicted and actual incident overpressures obtained.

The structure used in the tests was a modified version of the STR4 series produced by the Star Corporation. Overall dimensions of the building were 80 ft. long by 20 ft. wide by 12 ft. high. It was oriented such that the long side of the structure faced the explosion.

Figure 1 illustrates the construction phase of the building; Figure 2 is a view of one end of the building after construction had been completed. As may be noted, an access door was positioned in one of the side walls and, therefore, it was subjected to blast loads corresponding to incident overpressures. The door withstood the effects of the blast in all tests.

The walls and roof of the building consisted of 24 gage cold-formed metal panels having a static yield strength of approximately 80,000 psi. This represented an increase in panel thickness from the 26 gage panel normally furnished with this size building. The number of Z-shape girts were increased from one each side to two per side. The girt located at the 7 ft.-3 in. level, was that which is furnished with the building. The added girt was located between the existing girt and the floor slab at the 4 ft. level. In addition, the size of each girt was increased from 8x3x0.064Z to 9.75 x 4 x 0.1345Z.

Although their locations were not changed, the size of the roof purlins was changed from 8x3x0.064Z to 8x3x0.084Z. To be assured that the building would function properly and that any resulting damage would occur within the structural steel portion, the building foundation was made heavier based on footing reactions determined from the frame analysis computer program DYNFA (Ref. 3). In addition, the column footings were tied together by the floor slab to prevent relative lateral displacements of the footings. Except for the foundation, which will require further investigation, the increased cost of the superstructure (steel portion) is estimated to be approximately 20 percent of the basic building costs. As will be shown from the test results, this increased construction cost is relatively small in comparison to the increased protection afforded by the changes.

Unlike the other building components, the three interior rigid frames of the building were the same as those used in conventional construction. An interior frame was also used as one of the end frames of the building to evaluate it relative to the "post and beam" frame which was used at the opposite end of the building. The post and beam frame is usually used as end frames for pre-engineered buildings of this size. This type of frame obtains its strength to resist sidesway loads by its interaction with the side-wall panels, thereby producing diaphram action. The loads are transmitted between the frames, secondary members and the roofing and siding by conventional metal screws used in sheet metal building design. As will be shown, these screws functioned as required to provide the necessary load transfer, although the metal siding and decking was damaged.

Instrumentation consisted of electronic self-recording deflection gages, pressure gages, accelerometers and strain gages. Pressure gages were used to record blast loads acting on the exterior surfaces of the building as well as blast pressure leakage into the building and free-field pressures. The deflection gages were attached to the frames (for both vertical and horizontal movements), girts and wall panels The accelerometers were used as back up for measuring building motions as well as to determine accelerations. The strain gages were intended to be used to evaluate column reactions. Only the presure and deflection gages gave acceptable test data.

However, this data was quite extensive and was more than sufficient to analyze the test results. In addition to electronic equipment, both still and motion picture coverage was used to record both pre-and post shot damage as well as to view the structure response during an event. Motion picture cameras were located both within and exterior of the structure. Pre-and post-test hand measurements were made to record permanent displacements.

An interior view of the structure illustrating the deflection gage attachment to the various building members is presented in Figure 3.

Test Results

Table 1 summarizes the pre-engineered building test results, including the free-field pressures; frame, girt and panel displacements; and a brief description of typical damage for each test. Figures 4 thru 9 illustrate this damage.

A minimal amount of damage was incurred in Test 1 (0.27 psi) which consisted primarily of the enlargement of side wall panel screw holes along the panel seams. Some of the screws were found loose after the test. This damage was attributed primarily to the interaction between side wall frames and panels. The panels served as diaphragms in stiffening the frames against horizontal motion, thereby, reducing the sidesway of the structure. Since the post and beam frame has negligible capacity to resist horizontal movement, the resistance afforded to these frames by the panels was found to be a significant factor which when translated into design criteria could represent a major cost savings.

Small gaps were observed to have formed during the first test between the screws of roof panel seams. Although similar gaps were not apparent in the wall panel seams after the test, motion pictures taken from the structure's interior indicated that these seams did open and close repeatedly yet remained closed after the shock wave passed. It is theorized that the vibrational motions of the panels (both roof and walls) at their seams was the major source of the pressure buildup within the structure. The magnitude of this internal pressure increase was approxmiately 40 percent of the

free-field pressures at all pressure levels. The effects of these internal pressures were to reduce the deflections of the individual components (panels, girts, purlins) and, thereby, increase their capacity to resist higher exterior loads. The effects of the leakage pressures on the overall motion (sidesway) of the building has not been evaluated todate.

Similar damage was incurred in Test 2. In addition to the roof, small permanent gaps (Fig. 9) were formed at the panel seams of the rear wall. Also, the screw hole enlargements formed in the first test were further enlarged. Motion picture coverage showed the opening of the door during the test. The door was not locked during this test, and resistance to opening was provided solely by the hinges and striker. The pressure buildup in the second test was proportionally no greater than that of Test 1, although the door did not open in the first test. This is a further indication that the primary source of pressure leakage into the building is through the gaps formed at the seams.

More extensive structural damage was formed in Test 3. The front panel kinked (buckled) at points where it was supported on the girts; the front panel was slightly disengaged where it was attached to the foundation (Fig. 6). The latter damage was attributed to the structural inadequacy of the detail used for attaching the panel to the foundation. In this case small (3/4" x 3/4") tubular sections were embedded into the corners of the slab. The physical attachment was through a series of "pig tails" connected to the tube and embedded in the concrete. These pig tails failed; thereby, permitting the panels to separate from the concrete. A more rigid connection, probably using steel angles attached rigidly to the concrete by anchor straps, should be used. In addition, the heads of some of the screws were pulled through the paneling. This situation was modified by providing washers (Fig. 9) for those screws which were disengaged. The use of washers during construction would probably have eliminated this condition.

The major structural damage which occurred in Test 3 consisted of the bending of one of the column anchor bolts and the twisting and tearing of several of the girt angle connections to the columns (Fig. 4). The twisting

is principally attributed to the zee shape of the girts which does not lend itself to undergoing large deflections; particularly, since the panel attachment to the girts produces eccentric loads on the girts. The twisting of the girts was one of the major contributing factors in causing the angle connectors to tear. As with the previous test, the door was opened by the rebound and negative overpressures. In this case, the lock had been engaged and was not damaged upon opening the door. This was an indication that the movement between the door and door frame was of sufficient magnitude to permit the door to be released. Further opening of the door during a test was prevented by the mechanism shown in Figure 2.

The damage occurring in Test 4 was similar to that of the previous test but somewhat more severe. In addition, permanent deflections in the girts were recorded and several of the girt connection bolts failed (Fig. 5). The bolt failure did not cause any girts to collapse and was remedied by replacing the standard bolts with high strength bolts. The stronger bolts did cause enlargement of some bolt holes in subsequent tests.

The resulting damage of Test 5 was similar to the previous tests, except that plastic deformations were formed in the frames, girts and paneling.

Test 6 was essentially the same as Test 5, with equivalent damage. However, the major damage occurred to the rear side of the building, which in this test, was the side facing the explosion. Permanent frame deflections produced in prior tests were reduced in this test.

Evaluation of Test Results

An evaluation of the test results is discussed below.

The frame displacements given in Table 1 are peak horizontal displacements of the mid-frame at the roof level, and represent the peak sidesway of the building. It is interesting to note the displacement versus time response and its relationship to the blast pressure loading. Figures 10 thru 13 present plots of front wall pressure, rear wall pressure, and sidesway displacement

versus time for Test 1 (0.27 psi), Test 3 (0.74 psi), Test 4 (1.0 psi) and Test 5 (1.2 psi), respectively. It is seen that the peak reflected pressure on the front wall is about twice the incident value, as expected. The peak rear wall pressure is between 60 and 80 percent of the incident pressure, which is less than that expected. The negative phase of the pressure loadings was found to be a significant factor in the response for the structure.

The displacement curves for Tests 1, 3 and 4 show the sidesway buildup due to the loading with the negative (rebound) displacement being larger than the positive displacement, and the peak positive displacement occurring in the second cycle after all the blast loading was off the structure. This behavior can be explained by the phasing of the blast loading, as follows. The first positive peak is a result of the net positive loading on the building walls (front wall minus rear wall pressure). As the frame starts to rebound, the negative pressure on the front wall and positive pressure on the rear wall are both acting in the same direction and in phase with the rebound. This combination of events produced a peak negative displacement which is greater than the positive displacement. A second positive displacement, which is greater than the first positive displacement, is produced by the rebound of the structure from the negative displacement combined with the negative phase of the loading on the rear walls. At the higher pressure levels (Tests 5 and 6), the negative displacements was nearly equal to the positive displacement, as shown in Figure 13 (for Test 5). This is due to the plastic deformation in the frame.

Other factors which affected the frame responses are the buildup of internal pressure, resulting primarily from leakage through the seams of the paneling, and the responses of the secondary members (purlins, girts, wall and roof panels) relative to that of the frames. It is believed that these factors have the greatest impact on the frame response in the plastic response range.

To further evaluate the test results, a series of analyses were performed using the Dynamic Inelastic Frame Analysis, DYNFA (Ref. 3) for the 0.27, 0.74 and 1.2 psi pressure levels. The results of these analyses, compared to the test data, for the midframe sidesway are shown in Figures 14 through 16. The actual blast pressures recorded during the tests were used in these analyses. In addition, the axial load and bending moment capacity of the frame members were computed using the actual yield stresses of the steel used in their manufacture. Their stresses were determined

by tensile tests on samples of the material provided by the building manufacturer. It is seen that an excellent correlation of the first positive and first negative peak displacements were made for Test 1 and Test 3. However, the analysis for Test 5 yields peak displacements for the first cycle of response that exceeded the test values by approximately 25%. The difference between the analytical and test results is probably caused by the failure of the bottom anchorage of the front wall panel, which would have tended to relieve the loading on the structure.

In addition, the DYNFA analysis for Test 5 predicted the occurence of large plastic deformations (in excess of the design criteria in Ref. 3) in the blastward column and roof girder. The analysis predicted the occurence of the deformations in the initial stages of the response, when the frame members respond primarily in a local bending mode. However, there is no evidence of these severe local responses from the test results (measurements of transient and permanent displacements). Hence, it is concluded that the responses of the secondary members limited the loadings on the frame. In the actual structure, the frame is loaded by the reactions of the secondary members. When these members respond into the plastic range, the maximum loading on the frame members is limited to the ultimate resistance of the secondary members, which was substantially less than the peak pressures acting on the building. As the test results show, the limited loading reduced the local bending responses of the frame members to acceptable levels, thereby increasing the blast resistance of the building to higher pressure levels. To substantiate this, a building column was analyzed as a single degree of freedom system. The column was taken as a simple-fixed beam and analyzed for 1) the reflected pressures on the blastward wall of the building, and 2) the time history of the girt reactions computed by performing an analysis of a girt as simply supported beam spanning between columns and loaded by the reflected pressures. The pressure loadings utilized in these analyses were those recorded for Test 5. The analysis for the actual blast pressures yielded plastic deformations (corresponding to a ductility ratio of 6) nearly equal to those computed in the DYNFA frame analysis, whereas the analysis for the girt reactions yielded much smaller plastic deformations (corresponding to ductility ratios of 2).

Additional analyses on the effect of the secondary member responses relative to the frame response are underway using analytical models of the frame which include equivalent single degree of freedom representations of the secondary members.

The peak girt displacements given in Table 1 are relative to the girt support displacement at the frame columns. The ductility ratios and rotations associated with these displacements have been compared to the design criteria presented in Reference 2, as follows.

The 3.0-in. deflection for Test 3 (0.74 psi incident pressure) is within the elastic range (calculated peak elastic deflection of 3.4 in.), and represents a rotation of 1.4° which is between the reusable criteria of 0.9° and the non-reusuable criteria of 1.8°. The limited damage to the girt for Test 3 is consistent with this criteria.

The 4.7-in. deflection for Test 4 (1.0 psi incident pressure) corresponds to a ductility ratio of 1.4 which compares to the reusuable criteria value of 1.25 and is less than the non-reusuable criteria of 1.75. However, the rotation is 2.2° which exceeds the non-reusuable criteria rotation of 1.8°. Since twisting of the girts occurred, the girt would not be reusuable and the limiting rotation value of 1.8 appears to be reasonable. In this case the member is controlled by rotation rather than ductility.

The 4.8-in. deflection for Test 5 (1.2 psi incident pressure) corresponds to a ductility ratio of 1.4 which is between the reusuable (1.25) and non-reusuable (1.75) criteria values. Here again, extensive twisting of the girts occurred which would render the member non-reusuable which is consistent with the actual rotation of 2.3° compared to the criteria value of 1.8°.

To further evaluate the girt responses, single degree of freedom analyses were performed for the actual pressures on the blastward wall that were measured in Tests 3 and 5. The girts were analyzed as simply supported beams spanning between columns. Comparisons of the analytical and measured girt responses are given in Figures 17 and 18 for Tests 3 and 5, respectively. In both cases, the computed displacements are greater than the measured values. In fact, the analysis for Test 5 yields a ductility ratio of 3.6 and support rotation of 5.8 degrees which are far in

excess of the design criteria and which indicate that the girt should have collapsed. The discrepancy between measured and computed girt responses results from 1) the pressure buildup inside the structure, 2) the interaction between the girt and frame responses, and 3) for Test 5 primarily, the failure of the anchorage at the bottom of the front wall panel. The net effect of the above would be to be reduce the girt response.

The peak panel displacements are measured relative to the girts. The measurements are for the section of panel spanning between girts which is assumed to behave more or less as a fixed supported beam. The ductility ratios and rotations associated with these displacements have been compared to the design criteria presented in Reference 2, as follows.

The peak displacement of 0.6 inches for Test 1 corresponds to a ductility ratio of 1.76 (based on an elastic deflection of 0.34 for fixed-fixed span) which equals the non-reusuable criteria value of 1.75 in Reference 2. The support rotation is 1.4 degrees which is somewhat less than non-reusuable criteria value of 1.8 degrees. The absence of significant damage to the panel indicates that the design ductility criteria is somewhat conservative.

The measured response for Test 3 of 1.1 inches corresponds to a ductility ratio of 3.23 and a support rotation of 2.57 degrees. Both the ductility ratio and support rotation exceed the non-reusuable criteria and although kinking of the panel at the lower girt was observed, the structural integrity of the siding was still intact. The only failure associated with the siding was a partial failure of the anchorage at the base of the wall. These results tend to confirm those reported in Reference 4 for panel and deck blast tests.

The measured panel displacements for Tests 4 and 5 are plotted in Figure 19. The large displacements shown for the second positive peak correspond to ductility ratios of 7.1 and 11.2 for tests 4 and 5, respectively. However, the motion pictures of these tests show the anchorage at the bottom of the wall pulling out as the panel rebounds. Hence, it is conceivable that the destruction of the anchorage eliminates the fixity in the panel at the lower girt, thereby changing the behavior of the center panel span from fixed-fixed to

simple-fixed. In the simple-fixed condition, the elastic deflection of the panel is 0.64 inches and the recorded displacements then correspond to ductility ratios of 3.8 and 5.9 for Tests 4 and 5, respectively, which according to the results reported in Reference 4, are tolerable for the non-reusable design condition. The occurence of kinks between the girts in Test 5 indicates successive hinge formation in the panel without an instability failure occuring in the panel. It is also possible that some portion of the loading is being resisted by membrane behavior of the panel. However, it is believed that the membrane forces would fail the screw connections at the bottom and top of the wall, or at least, enlarge the screw holes to the extent that the membrane capacity of the panel would be severely limited.

Single degree of freedom analyses of the panel for the actual measured pressure waveforms yielded deflections far in excess of those recorded for all Tests. The discrepancy between measured and computed responses can be attributed to 1) pressure buildup within the structure and 2) interaction between the panel and girt responses. Analytical studies are being conducted to evaluate the second effect.

Conclusions and Comments

Based upon the foregoing, the following comments are offered:

1. Use of pre-engineered buildings to provide protection at overpressure ranges corresponding to inhabited building distances (Pso = 2.0 psi) is practical.

2. Some building modifications will be needed to insure that the blast resistant capacity of individual building components are consistent. This may require the substitution of larger members for members used for conventional loads, spacing of members may have to be reduced and/or the number of individual components may have to be increased.

3. Other building revisions may be necessary to develop the full capacity of the structure; these include:

   a. Provide washers or other means to prevent heads of screws from pulling through metal panels and roofing.

   b. Strengthen the connection of wall panels at the foundation.

   c. Use high strength bolts in place of standard bolts.

   d. If available as pre-engineered building components, use standard structural steel shapes for girts and purlins (avoid use of Z shape members).

   e. Increase size of anchor bolts to be consistent with the blast capacity of the structure.

   f. Provide a reversal mechanism on the door consistent with the blast capacity.

4. Dynamic analyses to evaluate the blast resistance of the main frames and secondary members (purlins and girts) of pre-engineered buildings should include the following effects:

   a. The negative phase of the blast pressure.

   b. The interaction between the responses of the secondary members and the frame responses.

5. The interaction between the sheet metal panels (siding and roofing) and their supporting members (girts and purlins) should be considered in evaluating the blast resistance of panels used on pre-engineered buildings.

6. The intereaction between the various secondary members and the building frames that were observed in the blast tests of pre-engineered buildings may not occur in steel structures designed for higher pressure levels. In these cases, the need for higher strength to resist the higher pressures may result in rigid members (panels, girts and purlins) which may not significantly interact with each other or the building frames. Hence, a test of a custom designed steel structure is needed to evaluate and refine, if necessary, the design criteria in Reference 2.

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TABLE 1 SUMMARY OF PRE-ENGINEERED BUILDING TEST RESULTS

Test No.	Free-Field Pressure (psi)	Peak Relative Horiz. Displacement (in.)			Damage
		Frame	Girt[a]	Panel	
1	0.27	1.7	0.8 1.0	0.6	(1) Enlargement of side wall panel screw holes. (2) Small gaps between screws of roof panel seams.
2	0.55	2.1	b 2.4	b	(1) Further enlargement of side wall panel screw holes. (2) Small gaps between screws of back wall panel seams. (3) Door opened outward.
3	0.74	3.1	2.5 3.0	1.1	(1) Bent anchor bolt. (2) Front Wall panel kinked along lower girt and pulled out at base at a few points. (3) Screw heads pulled through front wall panel at columns. (4) Some twisting and tearing of girt clip angles. (5) Door opened outward.

TABLE 1 SUMMARY OF PRE-ENGINEERED BUILDING TEST RESULTS (Concluded)

Test No.	Free-Field Pressure (psi)	Peak Relative Horiz. Displacement (in.) Frame	Girt[a]	Panel	Damage
4	1.0	3.8	4.7 4.1	2.4	(1) Further twisting and tearing of girt clip angles. (2) Shearing of some girt connection bolts without collapse. (3) Twisting of girts. (4) Front wall panel anchorage pulled out. (5) Further kinking of front wall panel. (6) Plastic deformations of girts.
5	1.2	4.1	b 4.8	3.8	(1) Further twisting of girts. (2) Kinking of front wall panel at each girt and between girts. (3) Front wall panel anchorage completely pulled out. (4) Panel screw holes pulled through at girts. (5) Plastic deformations of frame, girts, and front wall panel.
6	1.3	4.9	4.9[c] b	7.3[c]	(1) Damage to front wall panel and girts similar to Test 5. (2) Buckling of roof purlin webs. (3) Some buckling of frame girder flange. (4) Plastic deformations of frame, girts, and front wall panel.

[a] Values are given for upper and lower girts

[b] No measurements were made

[c] Questionable value

Fig. 1 Pre - Engineered Building Under Construction

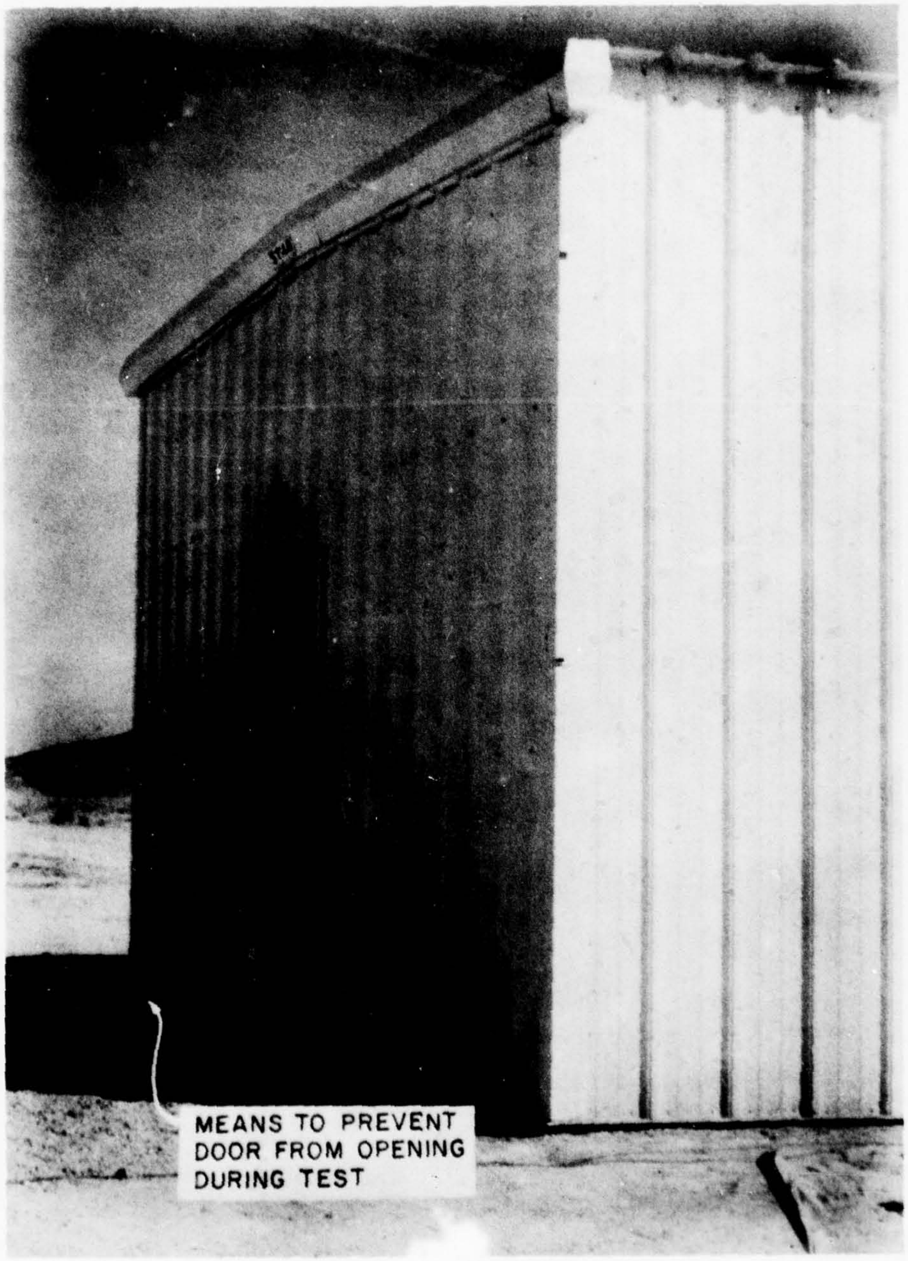

Fig 2 Exterior View of Completed Building

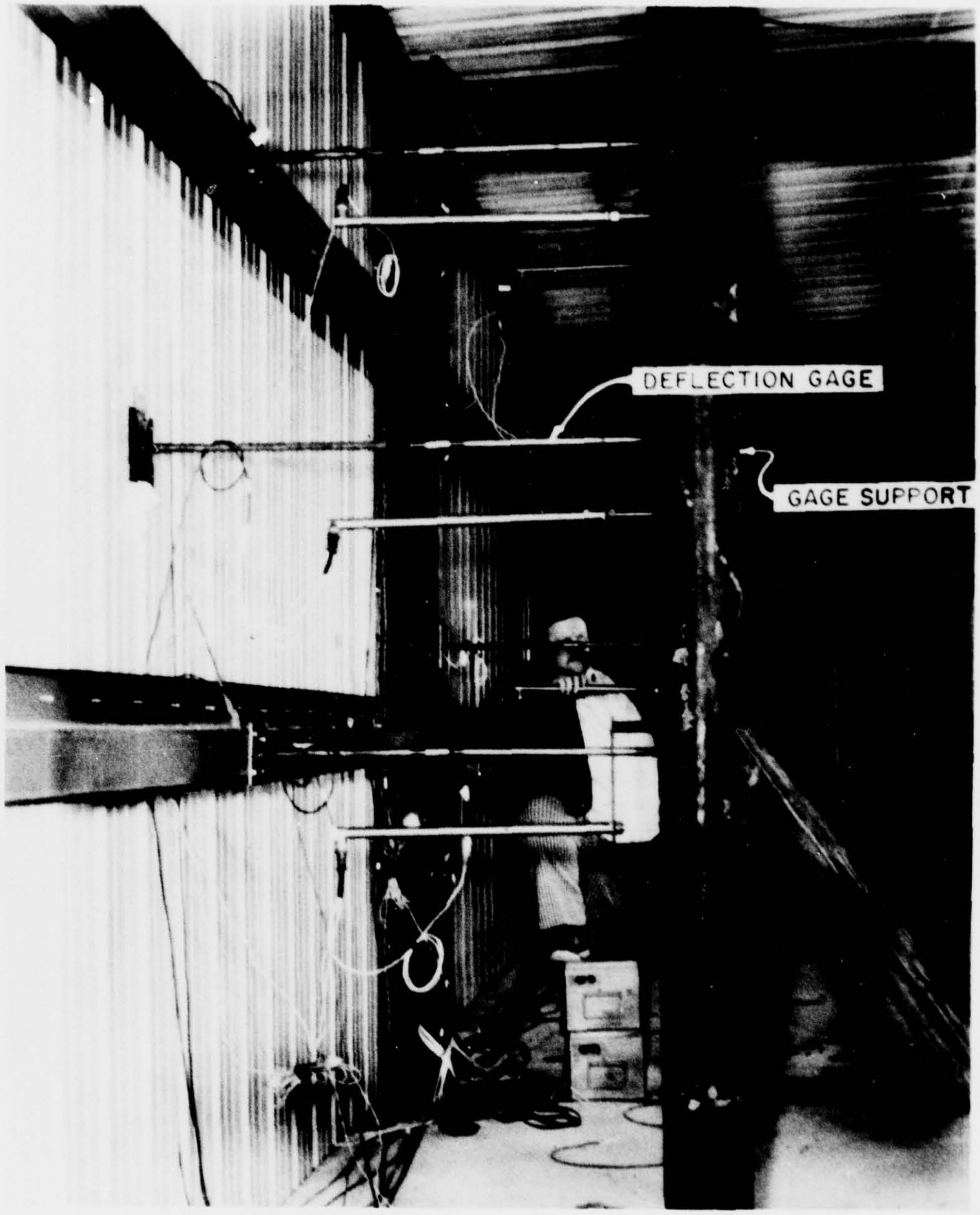

Fig 3 Interior View Showing Instrumentation

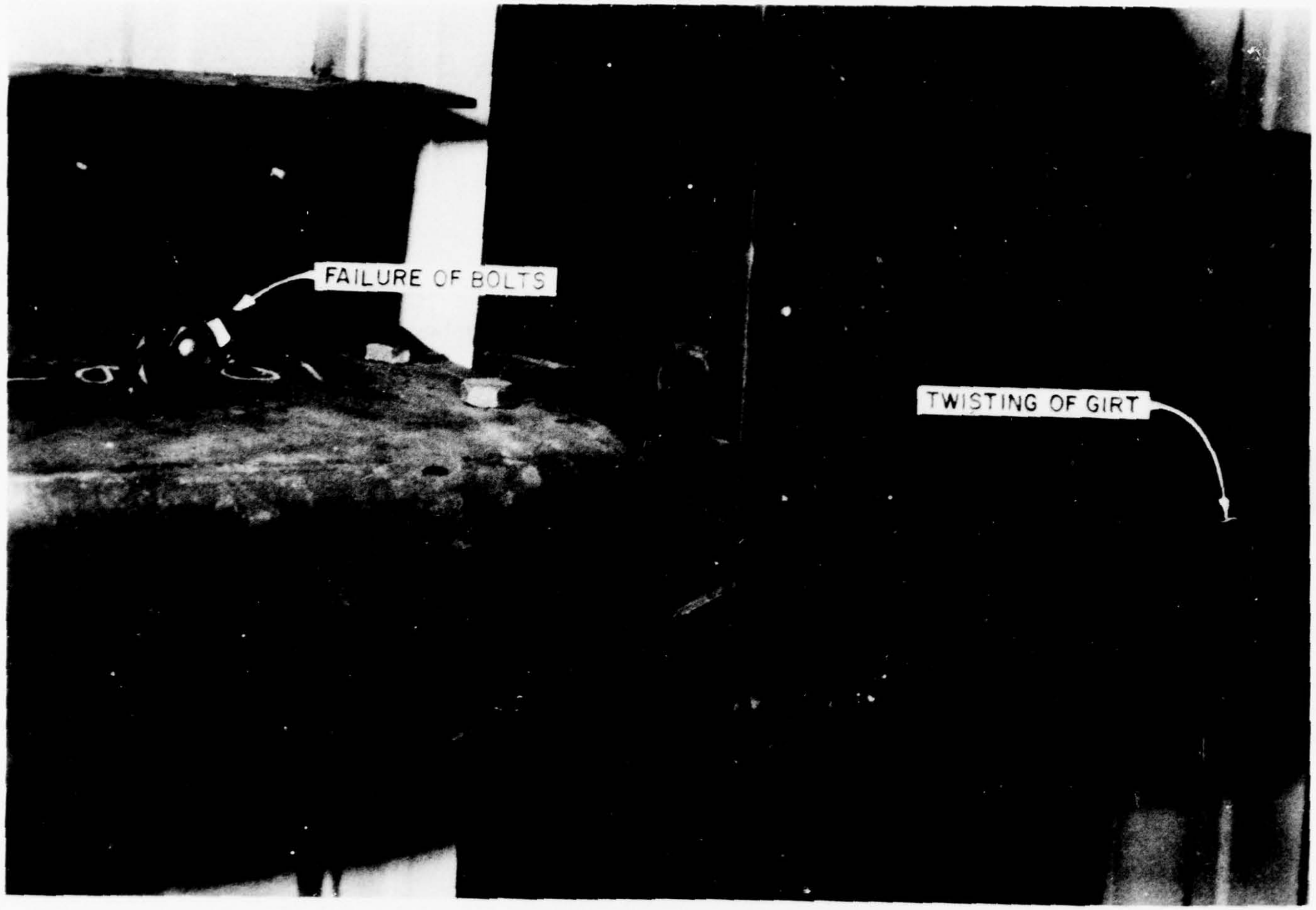

Fig 4 Damage to Girts and Connections

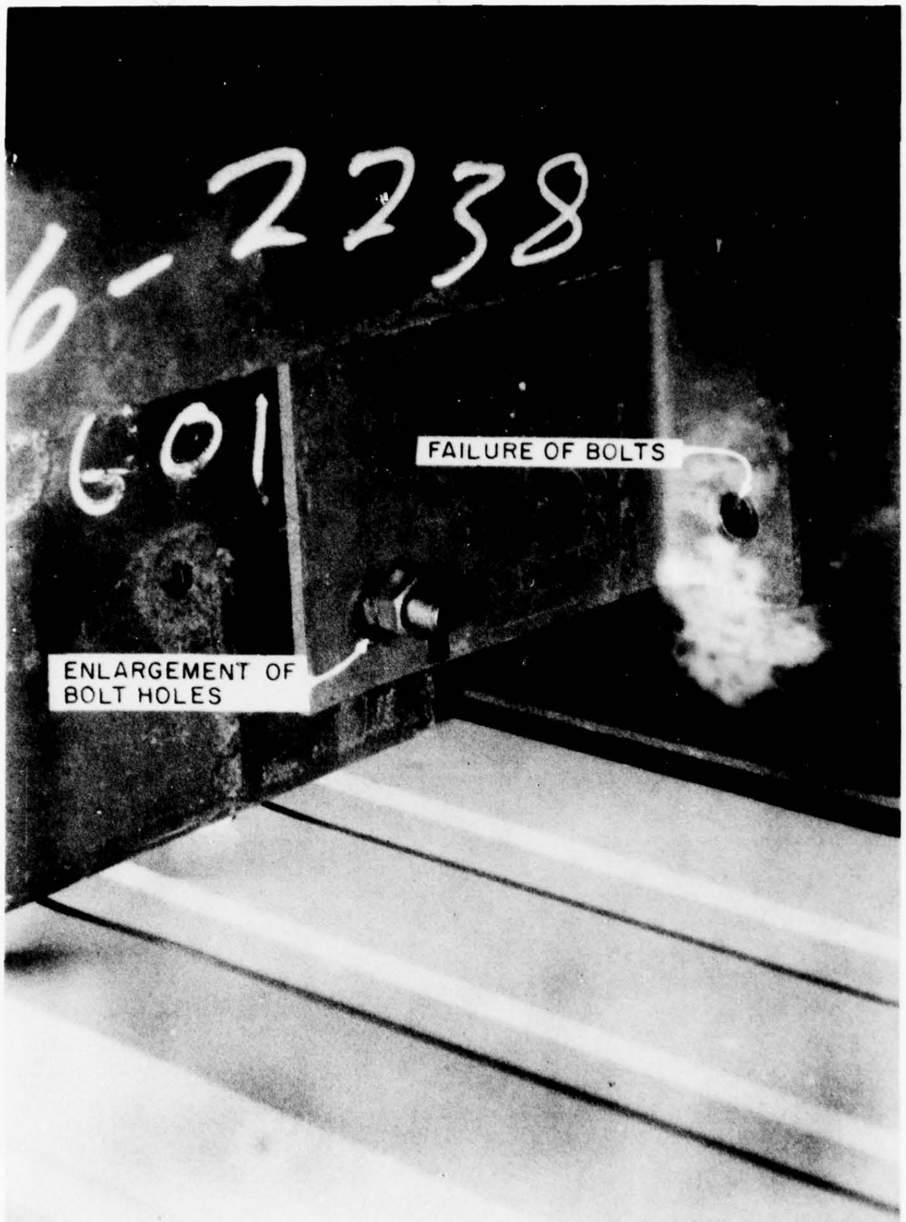

Fig 5 Tearing of Bolt Holes

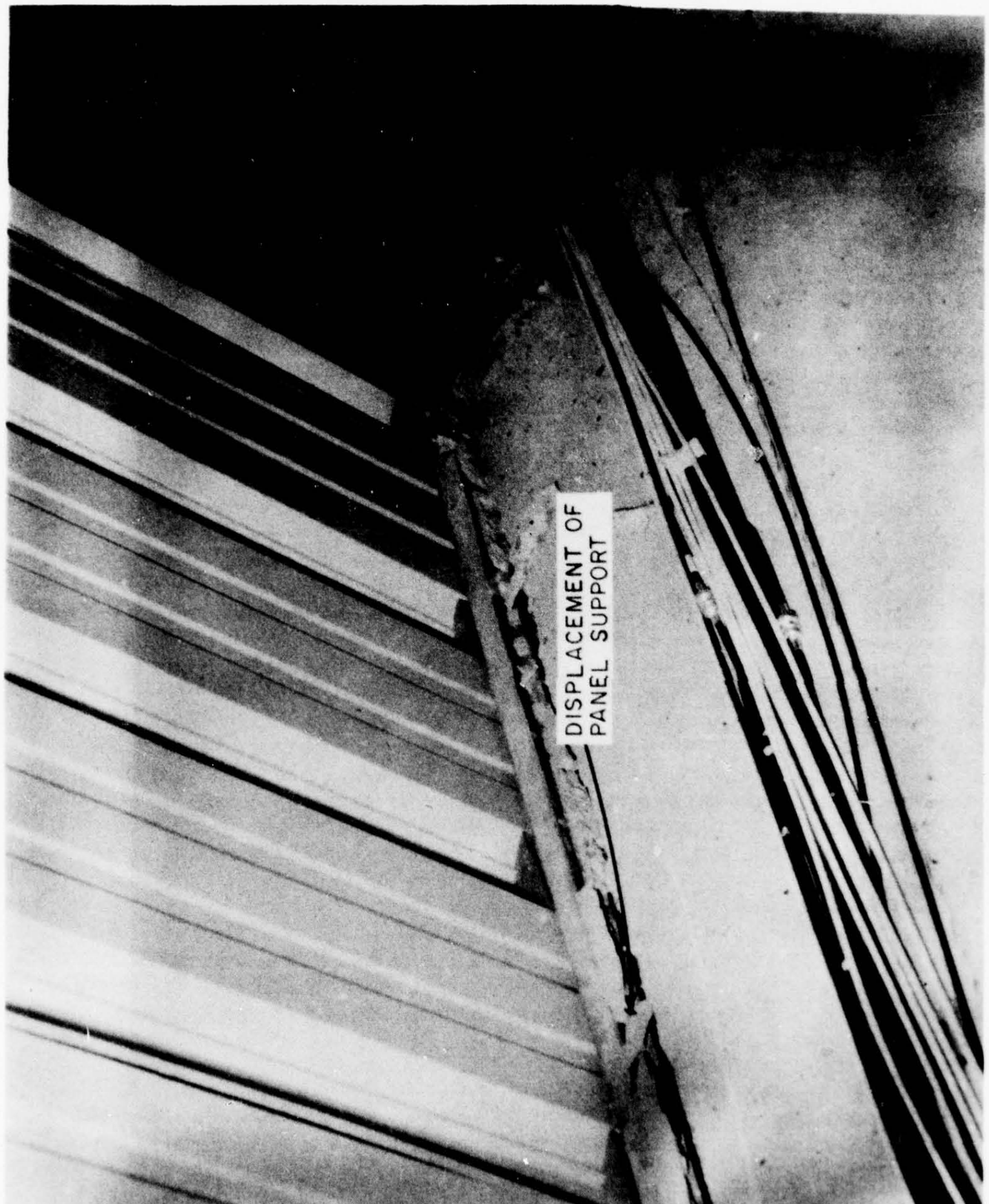

Fig 6 Pulling Out of Wall Panel Anchorage

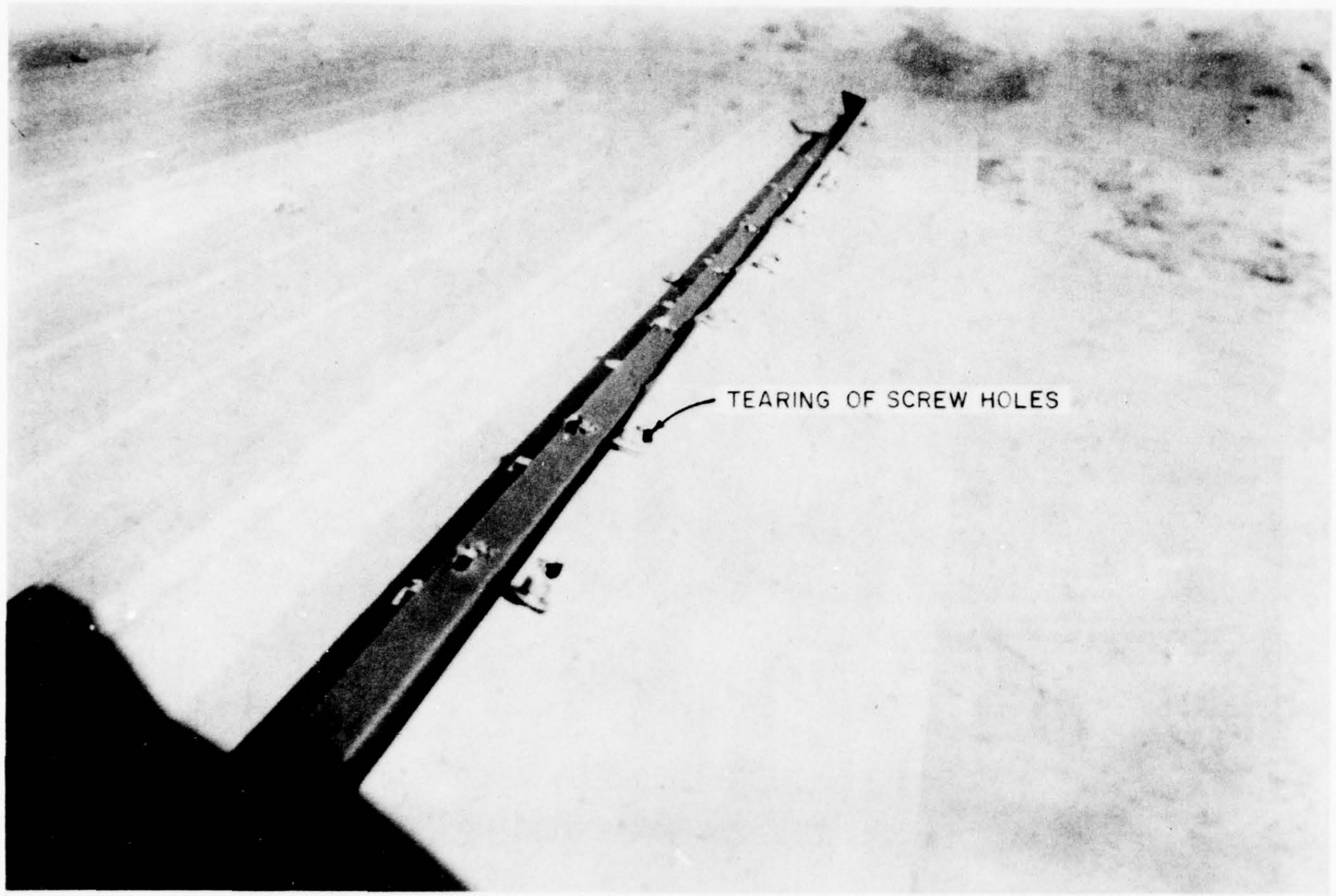

Fig. 7 Tearing of Screw Holes in Roof Panel

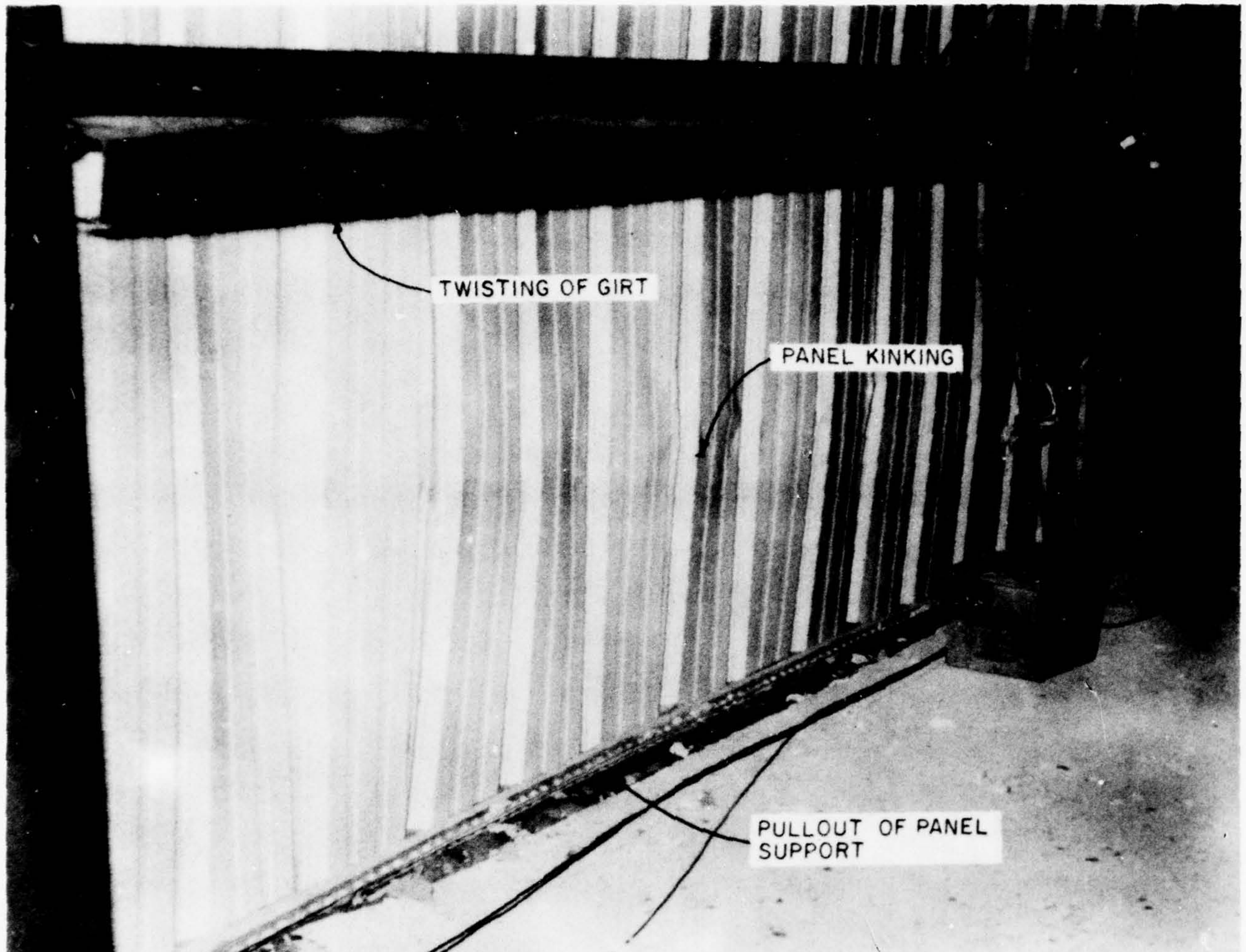

Fig. 8 Interior View Showing Damage

Fig. 9 Exterior View Showing Damage

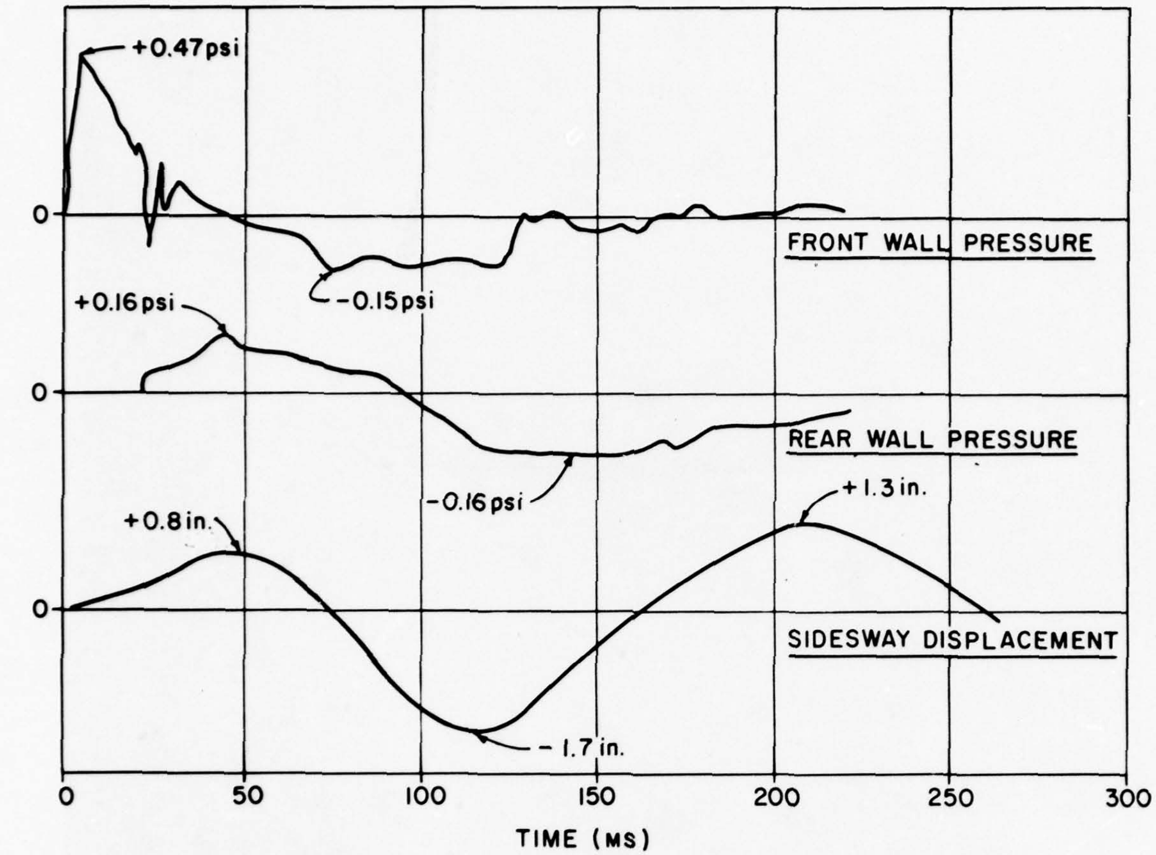

Fig 10 Measured Building Pressures and Displacement for P_{SO} = 0.27 psi

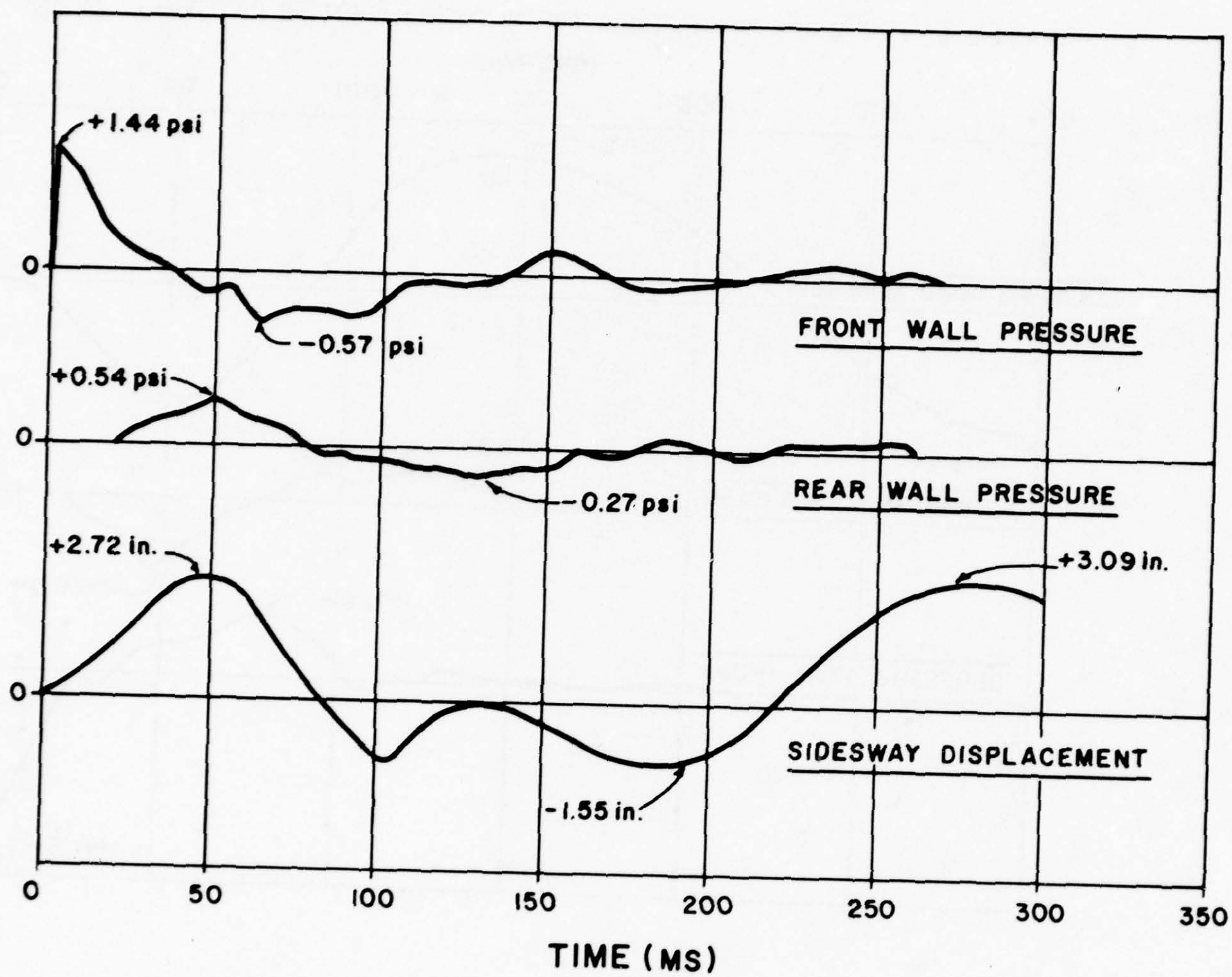

Fig 11 Measured Building Pressures and Displacement for P_{so}=0.74 psi

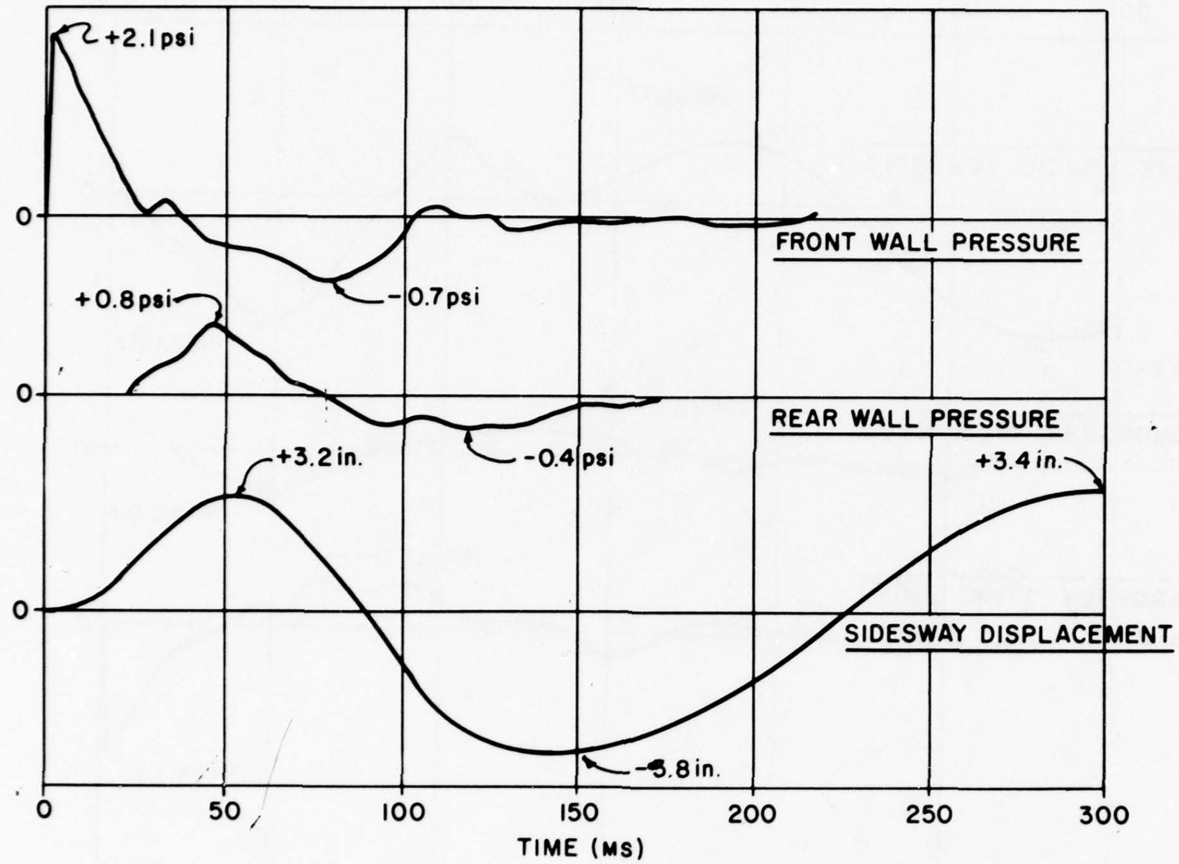

Fig 12 Measured Building Pressures and Displacement for P_{SO} = 1.0 psi

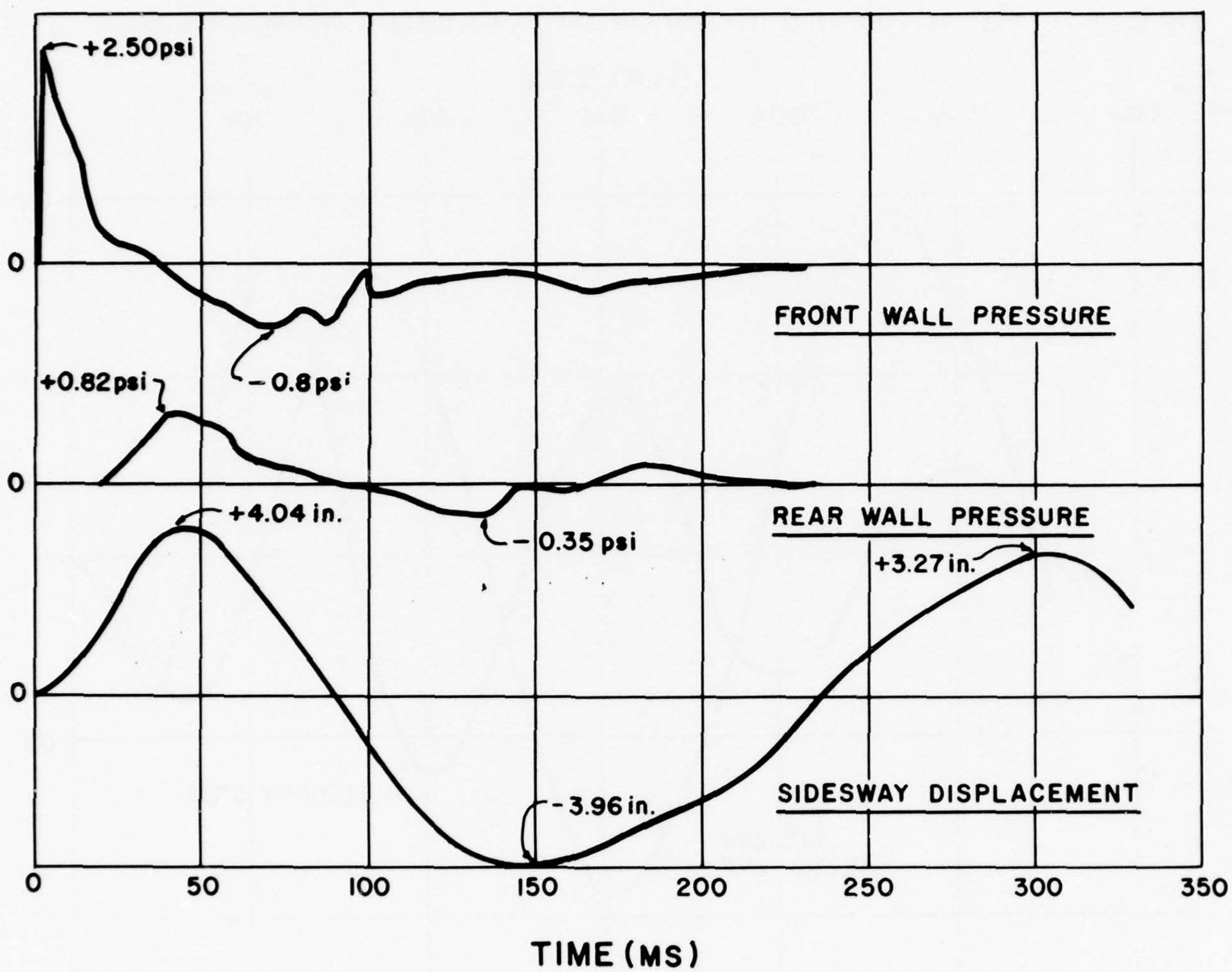

Fig 13 Measured Building Pressures and Displacement for $P_{SO}=1.2$ psi

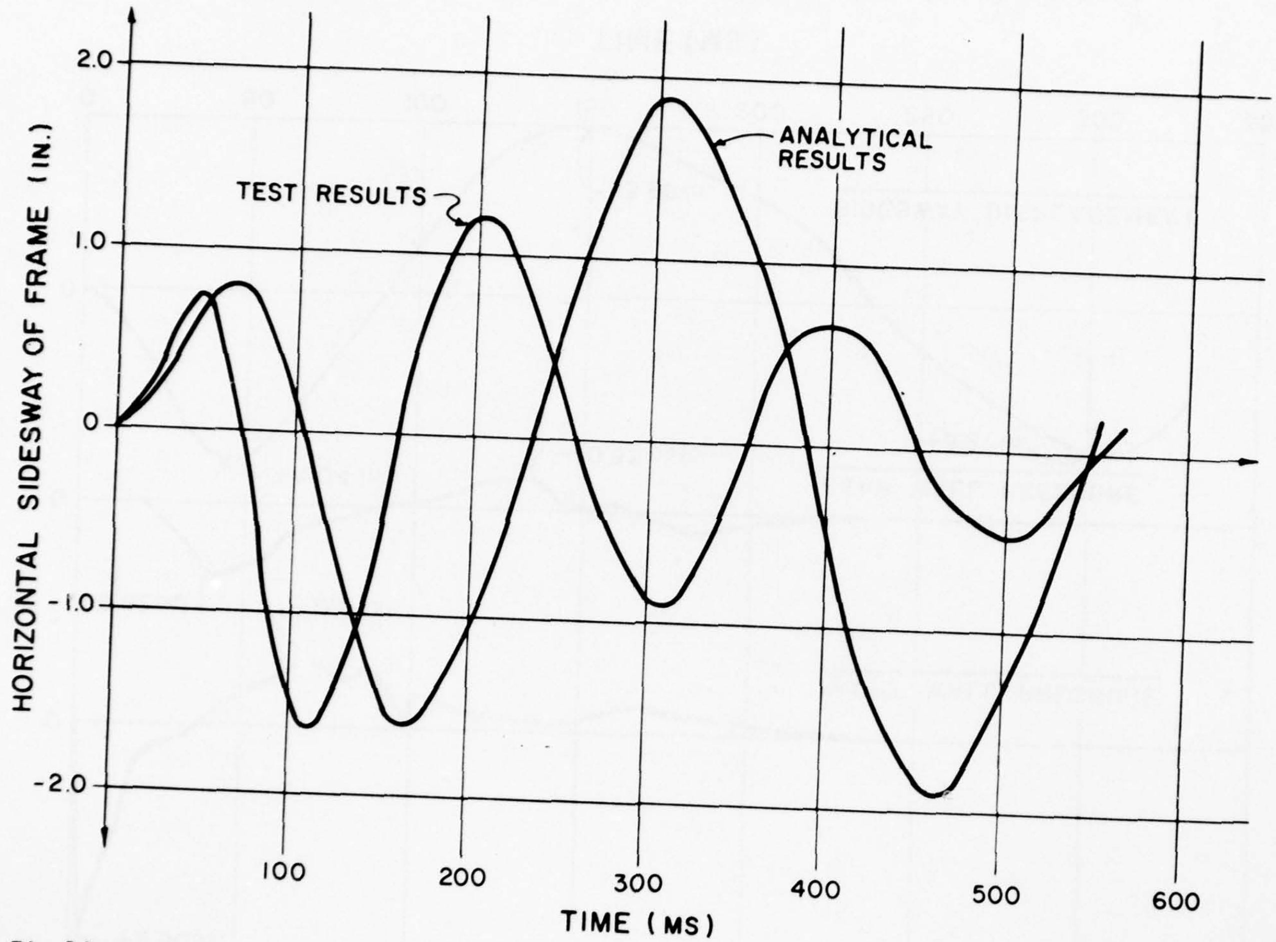

Fig 14 Midframe Sidesway Deflection - Test and Analytical Results for P_{so} = 0.27 psi

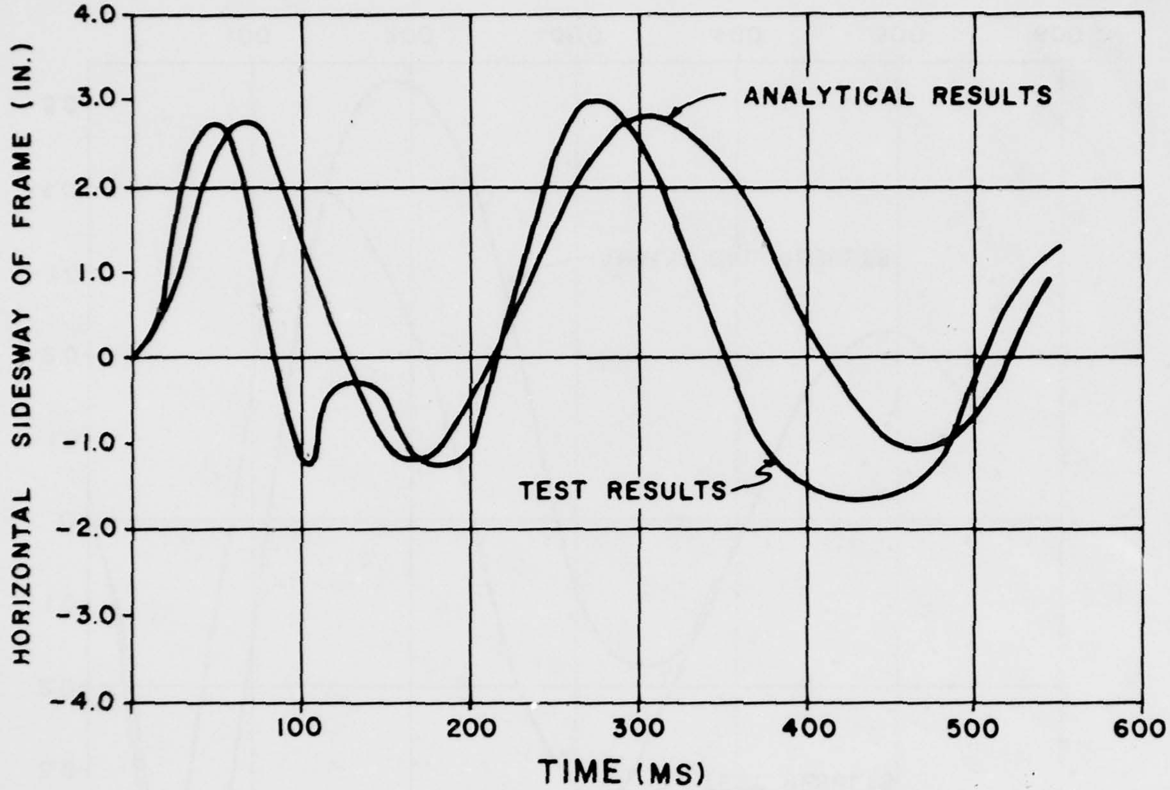

Fig 15 Midframe Sideway Deflection - Test and Analytical Results for P_{so}=0.74 psi

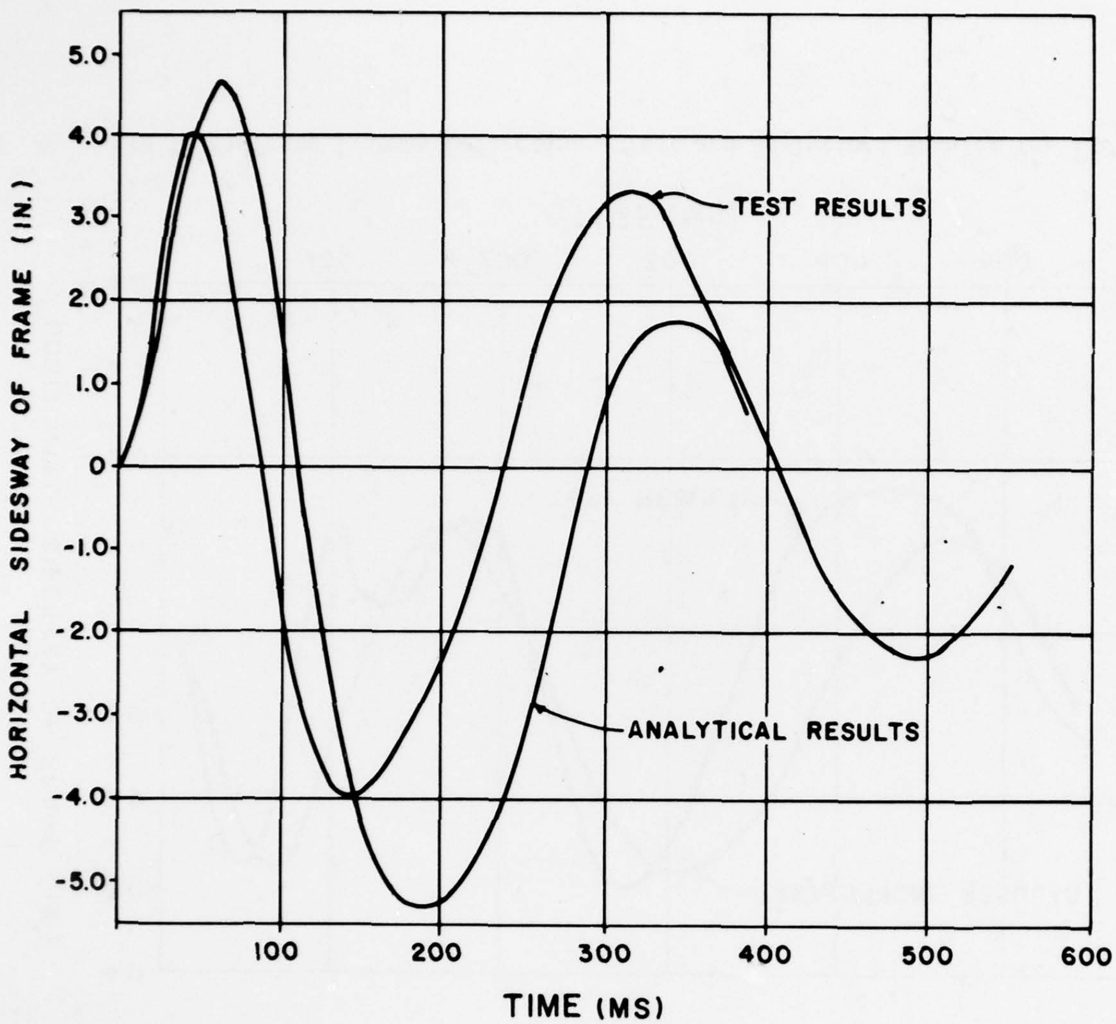

Fig 16 Midframe Sidesway Deflection - Test and Analytical Results for P_{so}=1.2 psi

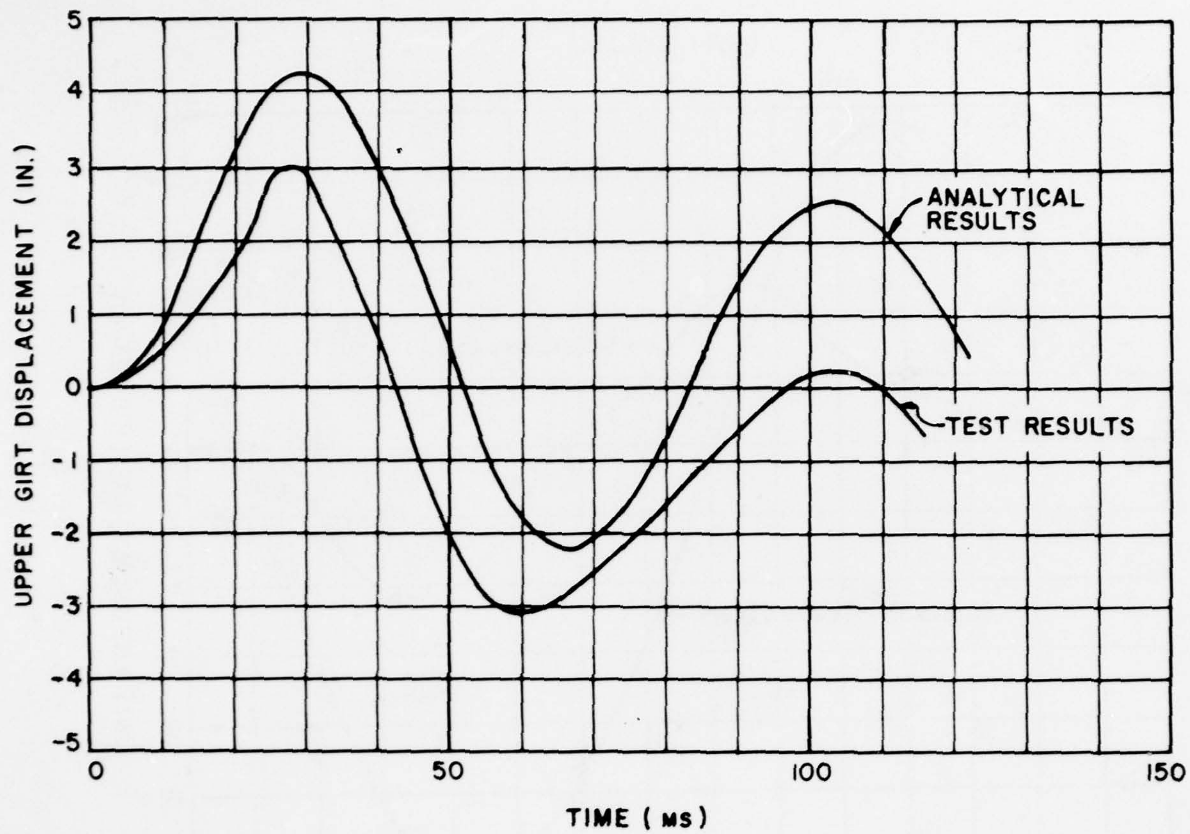

Fig 17 Upper Girt Displacement - Test and Analytical Results for P_{so}=0.74 psi

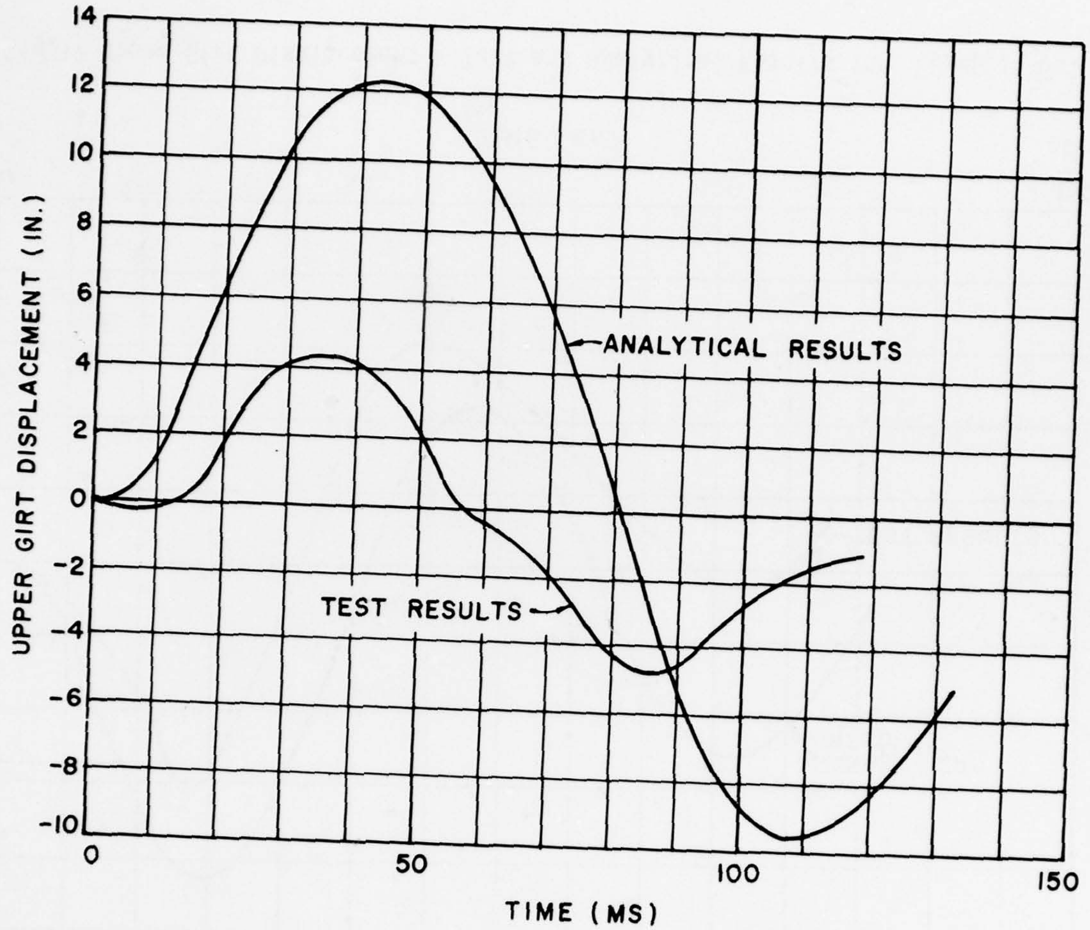

Fig 18 Upper Girt Displacement - Test and Analytical Results for P_{so}=1.2 psi

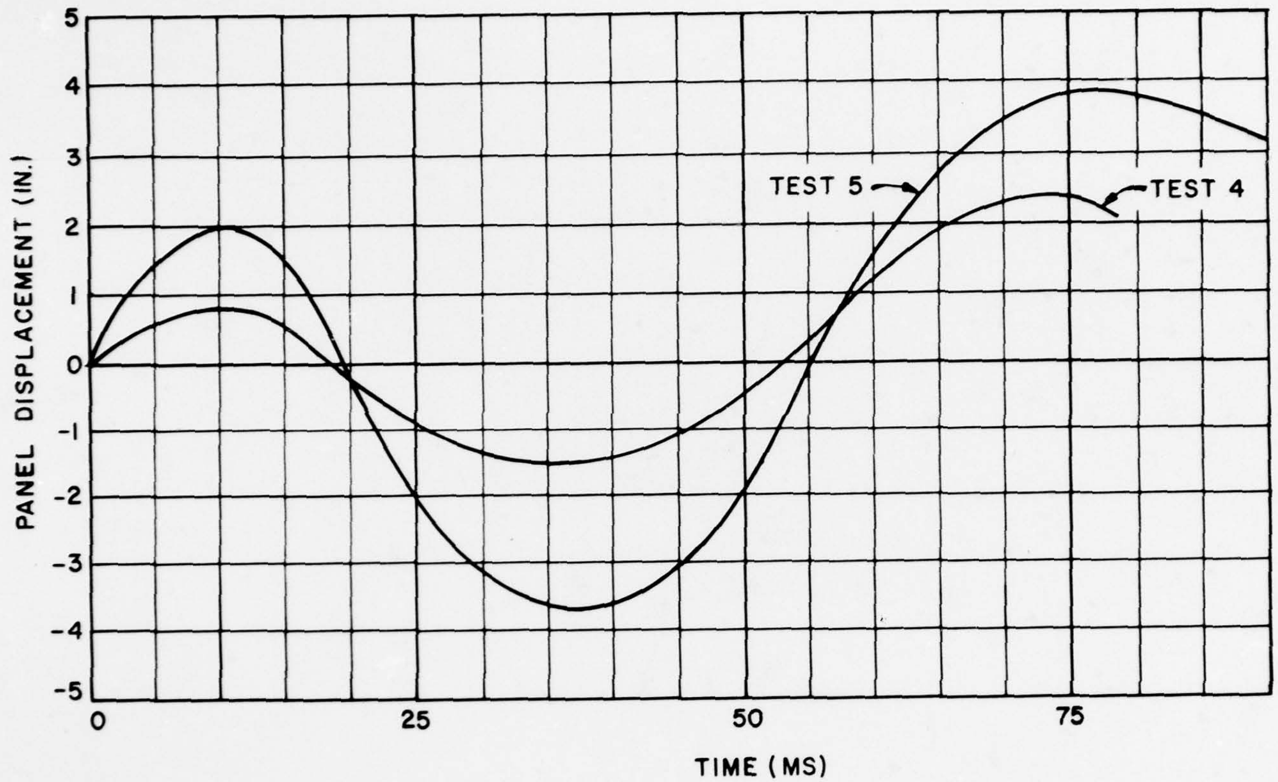

Fig 19 Panel Displacements - Test Results for P_{so}=1.0 and 1.2 psi

RESULTS AND ANALYSIS OF GLASS AND COLD FORMED STEEL BLAST AND STATIC TESTS

by

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ABSTRACT

This paper summarizes recent and on-going ARRADCOM tests for the development of design criteria and procedures for acceptor structures located in low to intermediate pressure ranges. Test procedures and results and design criteria are presented for both cold-formed steel panels, glass and glass window frames. The data presented supplements the data on acceptor structure design given in PTA reports 4837, 4838 and 4839.

TRADE NAME CITATION

The citation in this paper of the names of commercial firms or the names of commercially available products or services does not constitute official endorsement or approval of such commercial firms, products or services by the U. S. Government.

INTRODUCTION

The U.S. Army, under the direction of the Project Manager for Production Base Modernization and Expansion, is currently engaged in a multi-billion dollar program to modernize and expand its ammunition production capability. In support of this program, the Manufacturing Technology Division of the Large Caliber Weapons Systems Laboratory, ARRADCOM, with the assistance of Ammann & Whitney, Consulting Engineers, has, for the past several years, been engaged in a broad based program to improve explosive safety at these facilities. One segment of this program deals with the development of design criteria for explosion resistance protective structures.

Development of this design criteria has, in the past, been primarily concerned with structures located in the high pressure region close-in to an explosion. The basic document to evolve from this effort is the tri-service manual, TM5-1300, "Structures to Resist the Effects of Accidental Explosions," (REf. 1). This manual contains comprehensive information on the principle of protective design, the calculation of blast loadings, dynamic analysis, and detailed procedures for designing reinforced concrete protective structures.

It is common practice in the explosives industry, for process buildings associated with the same line, to be separated by "intraline distances" which are meant to provide a high degree of protection against the propagation of explosions from building to building. Similarly, the minimum distance permitted between an inhabited building, not associated with the line in question, and an explosives location is the "inhabited building distance". These distances are published in the DARCOM Safety Manual (DRCR 385-100) and are based on the cubic root scaling of the explosive weight which defines area of equal pressure. In all cases, however, the blast overpressures than an acceptor structure would see in the event of an explosion in the "building next door" would be greater than a conventional structure is designed to withstand and serious injury to personnel within them is likely. In this regard, explosive tests have been conducted to evaluate the blast capacity of glass windows and cold-formed steel panels. The results of these tests, which are described in this paper, have been used to verify and refine data contained in ARRADCOM technical reports pertaining to the design of acceptor structures (Ref. 2 and 3).

In general, acceptor structures relate to buildings located in pressure ranges to 10 psi or less. These buildings contain personnel and/or valuable equipment which require protection against the blast and fragment output of an accidental detonation, particularly where hazardous operations are involved. The selection of the appropriate structural materials for acceptor structure design depends on overpressure level, degree of fragment hazard, explosive contents of the acceptor building, and normal operational functions. In some cases, existing structures are utilized in the modernization and expansion program and it is necessary that criteria be available for the evaluation of such structures, to determine their adequacy or modifications required to obtain the desired protection. Criteria relevant to the blast capacity of glass windows is particularly important since glass breakage has been found to be a major cause of personnel injury resulting from explosive incidents.

This paper is organized in two main sections, namely, glass and window frames, and cold-formed steel panels. These sections summarize the results of the test recently conducted and compare the tests data with design criteria and analyses previously developed.

GLASS AND WINDOW FRAMES

General

The use of normal thickness glass (3/8-inch or less) and typical standard aluminum window frames in blast resistance construction will usually be limited to acceptor structures located at overpressures of 5 psi or less. However, where relatively small quantities of explosives are involved, applicable overpressure ranges may be as high as 7 to 8 psi. At closer ranges, however, the use of glass is not generally feasible and windowless structures will be required.

Glass used in blast resistant structures can be separated into two categories: (1) regular glass which is that glass used in normal home construction, and (2) tempered glass which consists of regular glass whose properties have been proportionally controlled and has been rapidly cooled from near the softening point (annealed) to increase its mechanical and thermal endurance. Tempered glass is commonly referred to as "safety glass".

In order to evaluate the blast resistance capacities of both regular and tempered glass and the window frames, a series of static and dynamic tests were performed (Ref. 4, 5 and 6). The static tests, the purpose of which was to evaluate ultimate static capacities of the glass and frames, were performed at Picatinny Arsenal; the dynamic test series was performed at Dugway Proving Ground as a part of the cold-formed steel tests discussed later in this paper. The latter tests were used to establish the blast overpressure levels which can be resisted by various thicknesses of both types of glass and the frames.

Static Tests

Static load tests were performed using both 1/4 in. regular and 1/4-in. tempered glass. Also, typical aluminum window frames, which would ordinarily be used in conventional construction were tested to determine whether their capacity was less than, equal to, or greater than that of the glass panes. To determine the glass capacity independently of the aluminum frame, the glass was tested in specially built wooden frames. The glass was also tested with the aluminum frames as a unit. Two sizes of aluminum frames were tested, namely: (1) small frames, each of which were 28-3/8 inches wide by 48 inches high, and (2) large frames each being 33 1/4

inches wide by 48 inches. For determining the capacity of the frame separately from that of the glass, a steel plate was substituted into the frame in place of the glass. The size of the glass tested was the same as the interior size of the large aluminum frame.

Figure 1 illustrates the aluminum frame utilized in these tests. It may be noted, that the frame consists of two parts: an outer stationary part which connects to a building, and an inner movable part containing the glass. The two sections are connected together with hniges and a latch. Both of these elements were tested to establish their load reversal resistance. The glass is connected to the inner frame with a standard "glazing bead". In order to provide weather protection, the bead is always located at the surface of the window facing the interior of a building. Hence the bead will be subjected to the direct effects of the blast wave. As will be shown, the bead has been found to be one of the critical elements in the frame/glass assembly.

Testing of the frames and glass was achieved with the use of a universal testing machine. Each window frame was supported on a special constructed steel support frame. Support was provided along the long sides of each window frame with the short sides remaining unsupported. The load on the frame and/or glass was aplied by the testing machine as a uniform load through a series of wood bearing blocks, plywood planks and thick padding material. The load applied to the specimen was automatically recorded by the machine. In the case of the aluminum frame test, the padding rested on the steel plate which simulated the glass, whereas in the glass tests the pads rested directly on the glass. Figure 2 illustrates a typical test setup for the static tests.

The items tested and the results of their tests are summarized in Table 1.

As may be seen, the failure mechanism for the frames was produced by excessive deformation of the glazing bead (Tests 1 thru 3). When the frame was strengthened by reinforcing the glasing beads with three metal screws at each side of the frame, the capacity of the frame was more than doubled. Based upon these results the ultimate capacity, for direct loading, was determined to be 2.9 psi for the standard frame and 6.0 psi for the strengthened frame.

Although the rebound strength (Test 5) of a standard frame was found to be equal to its strength to resist direct load, the latch was not capable of developing this rebound strength (Test 4). Therefore, modification to the latching system was needed since total closure of the windows was required. By increasing the strength of the latch to at least that of the rebound strength, the reversal strength that was required for the strengthened frame was furnished. If pressure leakage through the windows can be permitted, strengthening of the latch need not be required. In the event of a failure, the windows would collapse outward and, therefore, will not be a source of danger to the building interior.

When tested in the wooden frames, the 1/4-inch thick tempered glass failed at a ultimate capacity of about 8.5 psi (Tests 6 and 7), while failure of the regular glass occurred at 0.65 psi (Test 8). As will be shown, both of these static capacities compared favorably with the dynamic strengths of the glass.

Figures 3 and 4 illustrate failures of tempered and regular glass, respectively. These figures illustrate the shape contrast between the failure mechanisms for the two types of glass. As shown, the tempered glass failed in small pieces and the regular glass broke into large jagged sections; the latter mechanism probably being the more dangerous for personnel.

When tested in the aluminum frame, the tempered glass showed a marked reduction in capacity, i.e. a reduction to approximately 1/4 and 1/2 its ultimate capacity when the glass was tested in the standard (Test 10) and strengthened standard (Test 11) frame, respectively. In the case of Test 9, it was apparent that premature failure had occurred do to the popping out of the glazing bead which was not fastened securely.

Based upon the above, it is obvious that tempered glass is significantly stronger than regular glass. However, its strength is reduced when mounted in the aluminum frame. This latter fact is attributed to the distortions produced in the glazing bead by the applied load which causes the glass to rotate and bend at its support. The wooden frame held the glass tightly and thus reduced the support bending and twisting. As will be shown, this behavior also occurred in the dynamic tests.

Dynamic Tests

Blast tests of glass were performed as part of cold-formed steel panels tests at Dugway Proving Ground (4, 5 and 6). The tests were performed in two series: the first series consisted of five individual tests, all of which included tempered glass, while the second series consisted of regular glass tests and tests of tempered glass/aluminum frame window assemblies.

The test structures used to support the test specimens consisted of the two wooden box structures (A and B) also used to support the corrugated panels in the cold-formed steel panel tests (Fig. 5). Structure A had provisions for handling five glass panes and/or frames during any test. Structure B, on the other hand, could only handle four test items. One large and one small pane could be installed into each side wall of each structure. In addition, Structure A had provisions for installing a small pane in its front face, facing the blast. This latter specimen therefore was subjected to reflected pressures. Each structure was located at opposite sides of the gage line which in turn consisted of five electronic pressure gages (Figures 6 and 7).

Two types of tempered glass were used. Each type was produced by different companies and are commercially called Durasafe (D) and Herculite (H). Both 1/4-in. and 3/8-in. thick tempered and regular glass were tested. These were tested in large (l) and small (S) panes. The frames consisted of both the standard (F) type and the strengthened (FF) frame. The individual test items and their test results are listed in Table 2.

In the first four tests of the first series, all of the Herculite and Durasafe panes survived peak blast pressures ranging from 0.3 to 6.5 psi. However, in Test 5 one of the five 1/4-inch thick Durasafe panes failed at 4.4 psi. This latter test result was taken to be the upper blast capacity for the tempered glass. Of the regular glass panes tested, two panes failed: one 3/8-in. thick small pane and one 1/4-in thick large pane. Both failures occurred at the 0.8 psi incident pressure level. The thicker pane was located at the front of the structure and, therefore, was subjected to reflected pressures of short duration. In structure B of the second series, a small pane of Durasafe glass positioned in a standard aluminum frame failed. This

occurred at an incident pressure of 1.2 psi and was attributed to excessive deformation of the glazing bead. Also, in Structure B during the fourth test, a pane of Durasafe glass mounted in a strengthened frame failed at an incident pressure of 3.1 psi. Here again, failure was attributed to excessive deformation of the glazing bead.

Comparison of Test Results

An evaluation of the test results was made by comparing the results of the static tests with those of the dynamic tests. For this comparison (Table 3), the ultimate strengths of the various items statically tested was divided by the dynamic-load-factor (DLF) of the glass. These values were then compared with corresponding peak blast pressures obtained from the dynamic tests. As may be seen from Table 3, that with the exception for the 1/4-inch thick regular glass, good agreement was obtained. In the case of the latter, it should be pointed out that the capacity of regular glass as specified by the manufacturers is based upon a 50-percent breakage probability which in itself would explain the test variations.

Results of the dynamic tests of regular glass were compared with data contained in other sources; including the results of ESKIMO II and ESKIMO III high explosive tests and wind data obtained from glass manufacturers.

The results of the ESKIMO tests have been summarized in Tables 4 and 5. These tests were conducted on standard (untempered) plate and sheet glass panes mounted in fixed and non-fixed frames. Pane sizes included 45 in. by 45 in., 42 in. by 20 in., 34 in. by 48 in. and 48 in. by 90 in. Panes were approximately 1/8 in. and 1/4 in. thick. All windows faced ground zero and were, therefore, subjected to reflected overpressures. Based upon ESKIMO II test data, the blast capacity for regular glass lies between 0.44 psi and 0.83 psi. ESKIMO III data suggests that the upper limit is closer to 0.60 psi. The ARRADCOM failure lack of 0.78 psi (Table 3) recorded for the dynamic tests on regular glass falls within this range.

Most glass manufacturers publish data for glass capacity under wind loadings. Such data for Herculite tempered glass (Ref. 7) is illustrated in Figure 8. The large glass size tested had an area of about 20 sq. ft.). For this area

and a glass thickness of '4 in., the wind load capacity is approximately 1.8 psi. Using a safety factor of 2.5, the ultimate capacity is 4.5 psi which is almost identical to the failure load of 4.4 psi from Table 3. Figure 9 shows corresponding wind load capacity data for regular glass. For a 1/4 in. thick pane of regular glass having an area of 20 sq. ft., the capacity is equal to 0.396 psi (or 57 psf). Using a safety factor of 2.5, the corresponding ultimate capacity is 1.0 psi. This value is higher than the 0.78 psi capacity of Table 3. However, it should be noted that the safety factor of unity used in the glass industry terminology corresponds to the wind load at which the probable number of panes that will break is 50 percent of the number subjected to the load. For a safety factor of 2.5, the probable number of panes that will break reduces to 8 out of 1,000 subjected to the load.

Data is not available to directly compare the static test results of the window frame with those of the dynamic Tests. However, an indirect comparison can be made by first dividing the static capacity of the frame by the DLF of the glass and then comparing this value with the results of the combined glass/frame tests of the dynamic series. This comparison shows good agreement.

Criteria

Based upon the results of the static and dynamic tests and on the above comparison, criteria were developed for both the glass and the aluminum frames used in these tests. Table 6 presents the glass criteria in terms of allowable peak pressure (incident or reflected) and load duration of a triangular shape pulse. Included are regular and tempered glass ranging in thickness from 1/8 to 3/8 inch. In the above criteria, the blast capacities for the 1/8-inch panes were extrapolated from the test results and from data pertaining to relative strength under wind loadings obtained from other sources. Further testing of 1/8 in. regular glass will verify or establish the conservatism of the criteria presented for this thickness.

The criteria for glass mounted in aluminum frames is presented in Table 7. This data is specific for those frames used in the tests but may be extended to include frames of similar shape and strength. Static tests should be performed to obtain criteria for frames which significantly differ from those tested.

The above criteria for either the glass or the frame, whichever specifies the lowest capacity, should be utilized for design.

COLD FORMED STEEL PANELS

General

Cold-formed steel panels are widely used for roof decking and siding in the construction of steel structures and pre-engineered buildings at explosives manufacturing and storage facilities. The behavior of these panels differs significantly from that of hot-rolled structural members, such as wide-flange beams, due to the cross-sectionsl shapes which are comprised of thin plate elements having large width-thickness and depgh-thickness ratios. Refer to Figure 10 for typical panel cross-sections. Under static loading, it is known that the load deflection curve for cold-formed panels is markedly non-linear and strongly dependent on the extent of local instability; and the effective properties are obtained by accounting for the post-buckling strength of stiffened flanges. For static design, the AISI Specification for the Design of Cold-Formed Steel Structural Members (Ref. 8) provides the necessary design guidelines. However, consideration of the blast-resistant capacity of such panels requires additional provisions.

Because of the large width-thickness and depth-thickness ratios, standard plastic design techniques are not directly applicable to cold-formed panels. However, for the purpose of blast design it is possible to account for a limited, but definite amount of plastic behavior. By permitting plastic (permanent) deformations, greater economy is achieved since lighter sections can be used in the design. The amount of plastic deformation which is acceptable will vary in magnitude depending on the function of the building and its intended reusability or non-reusability after an accidental explosion.

Criteria have been developed by ARRADCOM for inelastic design of cold-formed sections subjected to blast overpressure. This criteria is presented in detail in Reference 2, and includes equations for ultimate moment capacities, ultimate resistances of single and continuous spans, stiffnesses, periods of vibration, shear stresses, support reactions, and rebound effects. In order to verify or refine the design criteria and determine the dynamic capacity of various panel sections and connection details, blast tests were performed as described below.

Test Description and Results

As previously stated, blast tests of cold-formed steel panels were performed as part of the dynamic glass tests at Dugway Proving Ground (Ref. 4 and 9). In these tests, single-span and three-span continuous panels were subjected to overpressures ranging from 0.3 to 15 psi, produced by detonating 2,000 pounds of high explosives. The positive phase duration of the overpressure was about 50 msec.

Cold-formed steel panels are manufactured in either open sections forming continuous corrugations, or closed sections consisting of a flat sheet with a series of hat sections. Both of these types of panels, which are shown in Figure 10, were tested. The Sec. 3, UKX and NKX panels, manufactured by the H.H. Robertson Company, are used in conventional buildings as roof decking. The 4-inch ribbed panel, manufactured by the Elwin G. Smith Division of the Cyclops Corporation, is used for siding. Similar cold-formed sections are manufactured by other companies.

Four test structures of two different configurations were used to support the panels in the tests. Two of the test structures (A and B) were wooden box structures 17 ft. long, 7 ft. wide, and 8 ft. high as illustrated in Figure 5. As previously mentioned, these structures were also used to test glass window panes and aluminum window frames. As shown in Figure 5, steel panels were mounted on the roof and front wall of Structure B. The roof was used to test three-span panels, 15 ft. long by 4 ft. wide. Steel beams were provided under the panels to obtain rigid supports for the panels. The front wall of Structure B was used to test single-span panels, 4 ft. - 6 in. long by 4 ft. wide. Structure A is similar to Structure B except that the front wall was used to test a glass window pane rather than a steel panel.

The other two test structures (C and D) were low wooden support structures, illustrated in Figure 11, used to test three-span panels at higher overpressures. The panel size was the same as that tested on the roof of Structures A and B.

The four-foot wide test specimens were constructed from two, standard two-foot wide panels. The seam between the panels was secured by welding or sheet metal screws. Three types of connections, weld, screw and bolt, were used to attach the panels to the steel beams of the support structure.

Figure 6 shows a typical layout of the four test structures as seen from ground zero. Also shown are the gages for measuring free-field blast pressures, which were mounted on adjustable pipe stands to facilitate positioning and orientation. Seven trials were conducted utilizing M26E1 and T28E1 propellants as the primary charge and Composition C4 as the booster charge, for a total of approximately 2,000 pounds of explosives.

Table 8 presents a summary of the panels tested with their types of connection. The numbers following the Sec. 3, UKX and NKX designations refer to the plate thicknesses which range from 22 to 16 gage. The 4-inch ribbed panel thickness is 24 gage. The cross-sections for these panels are shown in Figure 10.

Table 9 lists the measured peak free-field overpressure at each structure for each test and the damage sustained by each panel.

Photographs depicting typical panel damage sustained in tests 5, 6 and 7 are shown in Figures 12, 13 and 14. All of the panels tested in the first five test remained elastic and, therefore, did not exhibit any permanent displacements. Figure 12 shows the damage to the Sec. 3-20 roof panel with screw connections of Test No. 7 (Table 9). This panel was subjected to 5.6 psi overpressure and sustained perminent bowing of 1.88 inches. This deflection in part was caused by the buckling of the panel's top flange. Figure 13 depicts the damage to the UKX 18-18 wall panel of Test No. 6. This panel had welded connections and was exposed to an incident overpressure of 4.5 psi and a reflected pressure of 10 psi. This panel sustained the largest permanent displacement (2.5 inches) of all panels tested. Figure 14 illustrates the damage incurred by the welded NKX 20-20 roof panel of Test No. 6. The panel was subjected to a peak overpressure of 9.5 psi and sustained a permanent displacement of 1.75 inches.

Evaluation of Test Results

Table 10 lists those parameters required for the analysis of the test results. The values of the peak pressure, fictitious duration (T), the maximum deflection (X_M) and the average stresses were obtained from the test data with the latter being obtained from static coupon tests. The values of the natural period (T_N), elastic deflection (X_E), required resistance (R_R) and the actual

resistance (R_A) was determined from modified procedures given in Reference 2. These modifications include the calculation of the natural period and the elastic deflection using the total rather than the effective moment of inertia and using the actual yield stress (average of several specimens) rather than the minimum stress.

It is seen from Table 10 that the average of the ratio of the required resistance to the actual resistance is equal to 1.155 and the root mean square is equal to 0.246 indicating that the method used for calculately the required resistance is slightly conservative. However, also indicated are values of ductility ratios and rotations which exceed those which are specified as maximum values reusable and non-reusable panels. Therefore, based upon these tests results and analyses, the following conclusions and recommendations for revised criteria of Reference 2 is offered:

1. The maximum ductility ratio criteria of 1.25 for reusable structures and 1.75 for non-reusable structures (Ref 2) can be increased to 3.0 and 6.0, respectively.

2. The maximum support ratio criteria of 0.9 degrees and 1.8 degrees for reusable and non-reusable structures (Ref 2) can be increased to 2.0 and 4.0, respectively. However, it should be realized that with the use of these larger rotations, permanent displacements similar to those of Figures 12 and 14 may be expected.

3. Future calculations for the natural period and for elastic deflections should utilize the total moment of inertia rather the effective moment of inertia of Reference 2.

4. The increased strength observed in the tests were due, in part, to the actual static yield stresses which exceeded the minimum stress at yield of 33,000 psi. The actual static yield stresses were found to range from 43000 to 57000 psi with an average of about 48,000 psi. Thus, this represents an average increase of about 40 percent over the minimum yield. Although this average increase can not be expected in all cold formed members, some increase in strength of the steel above the minimum should be considered in design. Therefore, it is recommended that where the actual yield is unknown a design stress equal to 40,000 psi be used. This represents an increase of 21 percent over the minimum: Cold-form steel of high strength

(e.g. minimum of 80,000 psi) will also exhibit an increased average yield stress. However, sufficient data is not presently available to recommend a design stress to be used.

5. Tests up to 5 psi have indicated that open hat section (Sec. 3 and 4-inch ribbed panels shown in Figure 10) can be used for applications in the low pressure range rather than only closed sections (UKX and NKX) and recommended in Reference 2.

6. Standard screw-type connections performed satisfactorily in blast tests up to 5 psi.

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TABLE 1

SUMMARY OF STATIC TEST RESULTS

Test No.	Test Specimens		Test Loads		Failure Mechanism
	Support[a] Frame	Item[b] Tested	Load (lbs.)	Pressure (psi)	
1	SA	Frame	2,425	2.87	Excessive defl. of glazing bead
2	SA	Frame	2,375	2.81	do
3	SA	Str. Frame	5,025	5.95	do
4	SA	Latch in Rebound	870	1.03	Excessive defl. of latch
5	SA	Frame in Rebound	2,375	2.81	Excessive defl. of frame
6	W	Tempered Glass	9,920	8.58	Glass breakage
7	W	Tempered Glass	9,600	8.30	Glass breakage
8	W	Regular Glass	750	0.65	Glass breakage
9	LA	Temp. Glass & Frame	1,175	1.02	Glazing bead popped out (premature failure)
10	LA	Temp. Glass & Frame	2,575	2.23	Glass breakage due to Excessive defl. of glazing bead
11	LA	Temp. Glass & Str. Frame	5,125	4.43	Glass breaking due to Excessive defl. of glazing bead

[a] SA - Small Alum. Frame, Area Tested = 844 in^2

W - Wood Frame, Area Tested = 1156 in^2

LA - Large Alum. Frame, Area Tested = 1156 in^2

[b] Glass thickness = 1/4 inch

TABLE 2

SUMMARY OF DYNAMIC TEST RESULTS

Series No.	Test No.	Incident Press (psi)		Type of Glass & Frames[a]									Breakage
				Stru. A Window No.					Stru. B. Window No.				
		Stru. A	Stru. B	1	2	3	4	5	1	2	3	4	
1	1	0.3	1.4	HS2[c]	HS3	HL2	HL3	HS2	HS2	HS3	HL2	HL3	None
	2	2.5	3.3	HS2	HS3	HL2	HL3	HS2	HS2	HS3	HL2	HL3	None
	3	1.2	4.3	DS2	DS2	DL2	DL2	DS2	HS2	HS3	HL2	HL3	None
	4	6.5	6.5	DS2	DS2	DL2	DL2	DS2	HS2	HS3	HL2	HL3	None
	5	4.4	4.4	DS2	DS2	DL2	DL2	DS2	HS2	HS3	HL2	HL3	1-DL2 (Stru.A)
2	1	0.3	1.0	RS2	RS3	RL2	RL3	RS3	--	FDS2	--	--	None
	2	0.3	1.2	RS2	RS3	RL2	RL3	RS3	--	FDS2	--	--	1-FDS2 & Frame[b]
	3	0.8	2.3	RS2	RS3	RL2	RL3	RS3	--	FFDS2	--	--	1-RS3 & 1-RL2
	4	1.3	3.1	--	--	--	--	--	--	FFDS2	--	--	1-FFDS2

[a] Definitions:

L - Large pane of glass

S - Small pane of glass

D - Durasafe tempered glass

H - Herculite tempered glass

F - Aluminum frame

FF - Strengthened Aluminum frame

[b] Glass breakage attributed to excessive deformation of glazing bead.

[c] Numbers 2 and 3 refer to 2/8 and 3/8 thicknesses.

TABLE 3

COMPARISON OF STATIC AND DYNAMIC FAILURE LOADS

Item Tested	Failure Load(psi)		
	Static	Static/DLF	Dynamic
Aluminum Frame	2.81	1.7	--
Strengthened Aluminum Frame	5.95	3.5	--
Tempered Glass (1/4 in.)	8.30	4.9	4.4
Regular Glass (1/4 in.)	0.65	0.38	0.78
Regular Glass (3/8 in.)	--	--	1.56[a]
Tempered Glass (1/4 in.) & Alum. Frame	2.23	1.3	1.2
Tempered Glass (1/4 in.) & Strengthened Alum. Frame	4.43	2.6	3.1

[a] Short duration reflected pressure.

TABLE 4

TESTS ON WINDOWS FROM ESKIMO II EVENT

p_{so}^{a} (psi)	p_{r}^{b} (psi)	t_{p}^{c} msec	Glass damage
0.54	1.10	158	All 10 panels broke. 8 of the panels were 1/4 in. ± thick and 2 were 1/8 in ± thick.
0.41	0.83	180	7 out of 8 panels broke. 6 of the panels were 1/4 in ± thick and 2 were 1/8 in ± thick. The panel which did not break was 1/4 in. ± thick.
0.22	0.44	202	None of the 8 panels six 1/4 in. ± and two 1/8 in. ± broke.

a p_{so} is the incident pressure

b p_r is the reflected pressure

c t_p is the duration of the positive phase. The reflected pressure duration is based on the clearing times and would be of less magnitude.

TABLE 5

TESTS ON WINDOWS FROM ESKIMO II EVENT

p_{so}^{a} (psi)	p_{r}^{b} (psi)	t_{p}^{c} msec	Glass damage
0.6	1.2	250	8 out of 10 panels broke. 8 of the panels were between 1/4 in ± and 1/4 in ± thick and 1 was 1/8± thick.
0.5	1.0	260	7 out of 8 panels broke. 5 of the panels were between 1/4 in ± and 1/4 in ± thick and 3 were 1/8 in ± thick.
0.3	0.6	290	3 of the 8 panels broke. One 1/4 in. ± and two 1/8 in. ± thick

a p_{so} is the incident pressure

b p_r is the reflected pressure

c t_p is the duration of the positive phase. The reflected pressure duration is based on the clearing times and would be of less magnitude.

TABLE 6

BLAST CRITERIA FOR GLASS MOUNTED IN ALUMINUM WINDOW FRAMES OF THE TYPE TESTED

Aluminum Window Frame	Peak Incident or Reflected Pressure(psi)				
	Triangular Load Duration(msec)				
	<1-10	10-20	21-40	41-100	>100
Un-modified	1.5	1.1	1.0	0.9	0.8
Strengthened	3.0	2.2	2.0	1.8	1.6

NOTES:

1. Blast capacities are applicable to glass area of 20 sq. ft. or less.

2. Blast capacities for the various load durations were extrapolated from test results based on relative dynamic load factors.

TABLE 7

BLAST CRITERIA FOR GLASS MOUNTED IN RIGID WINDOW FRAMES

Glass	Thick (in.)	Peak Incident or Reflected Pressure(psi)				
		Triangular Load Duration(msec)				
		<10	10-20	21-40	41-100	>100
Tempered	1/8	3.0	2.5	2.0	1.5	1.0
Tempered	1/4	6.0	4.5	4.0	3.0	2.5
Tempered	3/8	8.0	7.0	6.0	5.0	4.0
Regular	1/8	0.4	0.3	0.25	0.15	0.1
Regular	1/4	0.7	0.6	0.5	0.4	0.3
Regular	3/8	0.9	0.8	0.7	0.6	0.5

NOTES:

1. See Table 6 for limiting blast capacities where glass is mounted in aluminum window frames.

2. Rigid window frame provides continuous support for glass similar to that provided by wooden frames used in the tests.

3. Blast capacities are applicable to glass area of 20 sq. ft. or less.

4. Tempered glass shall meet the requirements of ANSI Z97.1-1972.

5. Blast capacities for the various load durations were extrapolated from test results based on relative dynamic load factors.

6. Blast capacities for 1/8 in. thick glass were extrapolated from test results based on relative strength under wind loading and relative dynamic load factors.

Table 8

COLD-FORMED STEEL PANELS

Test	STRUCTURE "A"			STRUCTURE "B"						STRUCTURE "C"			STRUCTURE "D"		
	Roof Panel[a]	Connection[b]		Roof Panel[a]	Connection[b]		Wall Panel[a]	Connection[b]		Roof Panel[a]	Connection[b]		Roof Panel[a]	Connection[b]	
		Type	Size		Type	Size		Type	Size		Type	Size		Type	Size
1	4-in. Rib 24 Gage	S	#14	UKX 20-20 Gage	W	3/4"	UKX 16-16 Gage	W	3/4"	UKX 20-20 Gage	W	3/4"	NKX 20-20 Gage	W	1"
2	4-in. Rib 24 Gage	S	#14	UKX 20-20 Gage	W	3/4"	UKX 16-16 Gage	W	3/4"	UKX 20-20 Gage	W	3/4"	NKX 20-20 Gage	W	1"
3	4-in. Rib 24 Gage	S	#14	UKX 20-20 Gage	W	3/4"	UKX 16-16 Gage	W	3/4"	UKX 18-18 Gage	TS	3/8"	NKX 20-20 Gage	W	1"
4	4-in. Rib 24 Gage	S	#14	UKX 20-20 Gage	W	3/4"	UKX 16-16 Gage	W	3/4"	UKX 18-18 Gage	TS	3/8"	NKX 20-20 Gage	W	1"
5	4-in. Rib 24 Gage	S	#14	UKX 20-20 Gage	W	3/4"	UKX 16-16 Gage	W	3/4"	UKX 18-18 Gage	TS	3/8"	NKX 20-20 Gage	W	1"
6	Sec. 3 22 Gage	W	3/4"	Sec. 3 18 Gage	W	3/4"	UKX 18-18 Gage	W	3/4"	UKX 18-18 Gage	TS	3/8"	NKX 20-20 Gage	W	1 ½"
7	Sec. 3 22 Gage	S	#14	Sec. 3 20 Gage	S	#14	Sec. 3 16 Gage	W	3/4"	UKX 18-18 Gage	TS	3/8"	NKX 18-18 Gage	W	3/4"

[a] See Fig. 10

[b] S - Self tapping screw
W - Puddle weld
TS - Threaded stud.

TABLE 9
SUMMARY OF TEST RESULTS

Test No.	STRUCTURE A			STRUCTURE B					STRUCTURE C			STRUCTURE D		
	Blast Pressure psi[a]	Roof Panel		Blast Pressure psi[a]	Roof Panel		Wall Panel		Blast Pressure psi[a]	Roof Panel		Blast Pressure psi[a]	Roof Panel	
		Type	Damage		Type	Damage	Type	Damage		Type	Damage		Type	Damage
1	0.30	4-in. Rib 24 Gage	None	1.0	UKX 20-20 Gage	None	UKX 16-16 Gage	None	1.5	UKX 20-20 Gage	None	2.0	NKX 20-20 Gage	None
2	0.31	4-in. Rib 24 Gage	None	1.2	UKX 20-20 Gage	None	UKX 16-16 Gage	None	1.9	UKX 20-20 Gage	None	2.9	NKX 20-20 Gage	None
3	0.78	4-in. Rib 24 Gage	None	2.3	UKX 20-20 Gage	None	UKX 16-16 Gage	None	3.1	UKX 18-18 Gage	None	4.0	NKX 20-20 Gage	None
4	1.3	4-in. Rib 24 Gage	None	3.1	UKX 20-20 Gage	None	UKX 16-16 Gage	None	4.0	UKX 18-18 Gage	None	5.6	NKX 20-20 Gage	None
5	2.0	4-in. Rib 24 Gage	2 Spans MD-.75"	4.5	UKX 20-20 Gage	1 Span MD-.75"	UKX 16-16 Gage	MD-.50"	5.6	UKX 18-18 Gage	1 Span MD-.25"	7.0	NKX 20-20 Gage	2 Span MD-.94"
6	3.2	Sec. 3 22 Gage	2 Spans MD-1.31"	4.5	Sec. 3 18 Gage	1 Span MD-.19"	UKX 18-18 Gage	MD-.25"	7.1	UKX 18-18 Gage	None	9.5	NKX 20-20 Gage	3 Span MD-1.75"
7	4.5	Sec. 3 20 Gage	1 Span MD-1.13"	5.6	Sec. 3 20 Gage	3 Spans MD-1.88"	Sec. 3 16 Gage	MD-1.88"	11.0	UKX 18-18 Gage	2 Spans MD-1.75"	15.0	NKX 18-18 Gage	2 Spans MD-.56"

[a] Data interpalated from Fig. 10.

TABLE 10

COMPARISON OF REQUIRED RESISTANCE WITH ACTUAL RESISTANCE

Test No.	Test Structure	Panel Location	Panel Type	Peak Pressure (psi)	Fictitious Duration (T) (ms)	Natural Period (TN) (ms)	T/TN	Elastic Deflection (X_E) (in)	Maximum Deflection (X_M) (in)	Ductility Ratio X_M/X_E	Avg. Yield[(a)] Stress ksi	Calculated Resistance (R_R) (psi)	Actual Resistance R_A (psi)	Resistance Ratio R_R/R_A
5	B	Roof	UKX 20-20	4.5	26	13	2.0	0.38	1.13	2.97	56.6	4.4	4.5	0.98
	B	Wall	UKX 16-16	11.5	16[a]	16	1.0	0.43	0.93	2.18	50.6	11.0	11.2	0.98
	C	Roof	UKX 18-18	5.6	24	12	2.0	0.42	0.67	1.58	60.4	7.0	7.3	0.96
	D	Roof	NKX 20-20	7.0	18	7	2.6	0.16	1.10	6.75	47.2	5.9	7.3	0.81
6	A	Roof	Sec 3-22	3.2	35	13	2.7	0.46	1.77	3.85	49.2	3.1	2.6	1.19
	B	Roof	Sec 3-18	4.5	32	12	2.7	0.43	0.62	1.44	46.5	6.3	4.5	1.40
	B	Wall	UKX 18-18	11.5	17[a]	12	1.4	0.35	2.85	8.20	50.4	7.7	8.5	0.91
	D	Roof	NKX 20-20	9.5	15	7	2.1	0.16	1.91	11.90	47.2	6.6	7.3	0.90
7	A	Roof	Sec 3-20	4.5	37	13	2.9	0.46	1.59	3.43	49.2	4.5	3.4	1.32
	B	Roof	Sec 3-20	5.6	35	15	2.8	0.46	2.34	5.10	49.2	5.1	3.4	1.50
	B	Wall	Sec 3-16	13.5	20[a]	13	1.6	0.48	2.36	4.90	46.6	10.8	7.3	1.48
	C	Roof	UKX 18-18	11.0	20	12	1.7	0.35	1.60	4.57	50.4	9.2	6.1	1.51
	P	Roof	NKX 18-18	15.0	8	7	1.2	0.16	0.72	4.50	45.5	11.5	10.6	1.08

(a) Avg. Stress of Top Hat

AVG. 1.155
RMS 0.246

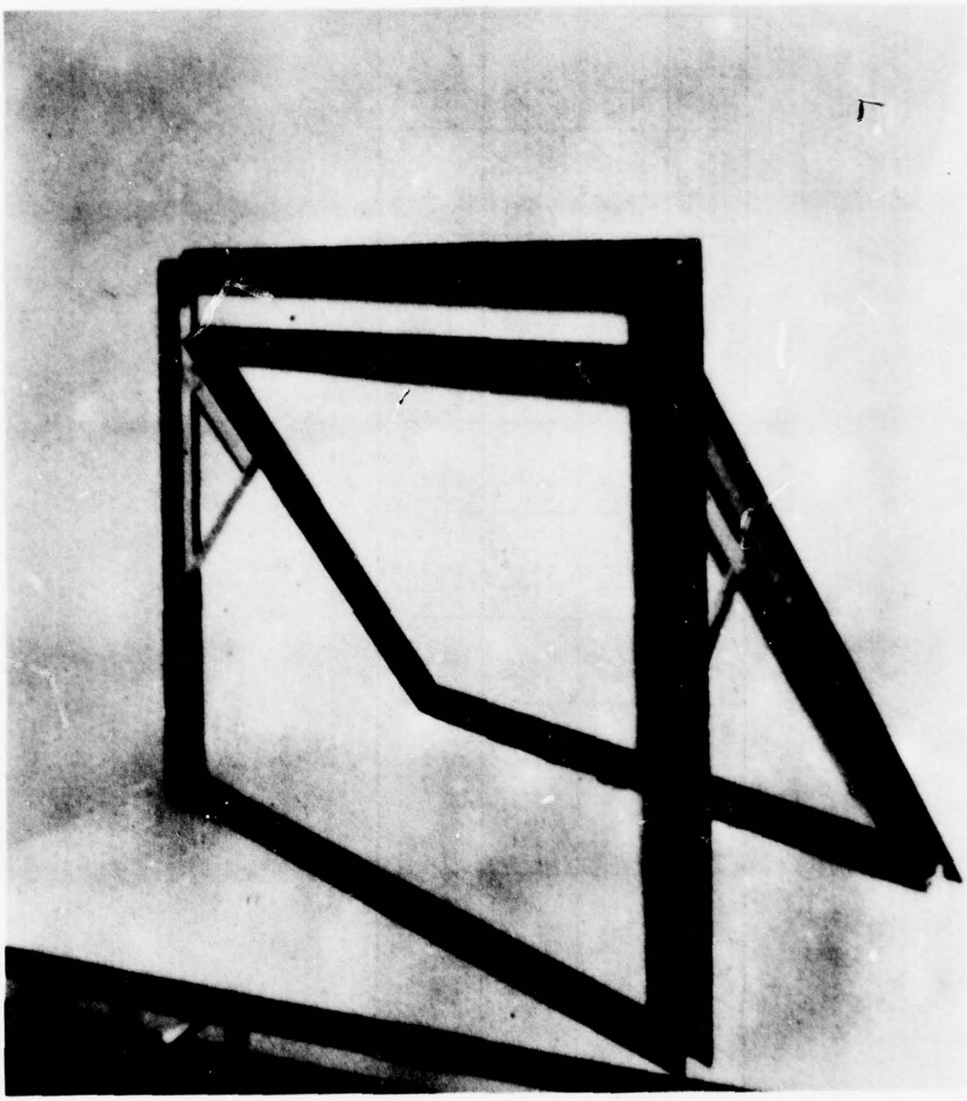

Fig 1 Typical Aluminum Frame

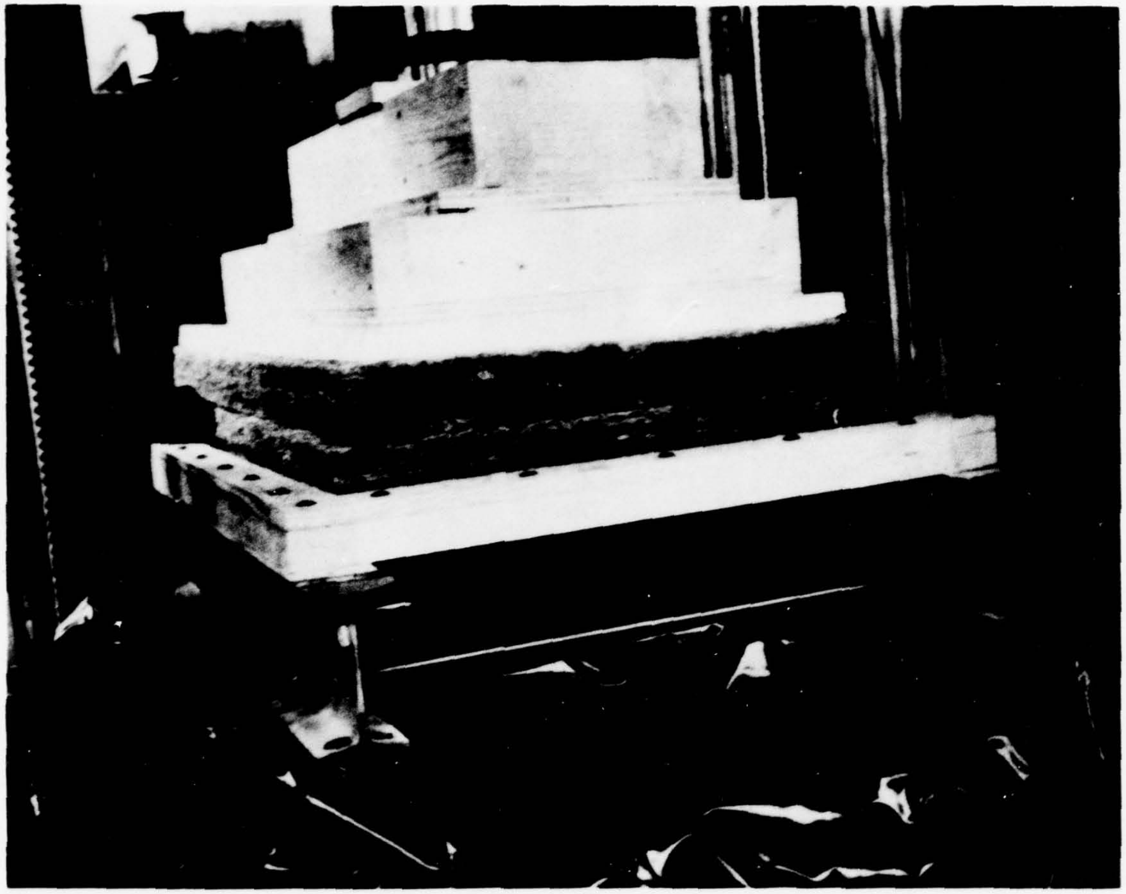

Fig 2   Test Setup for Static Tests of Glass Panes

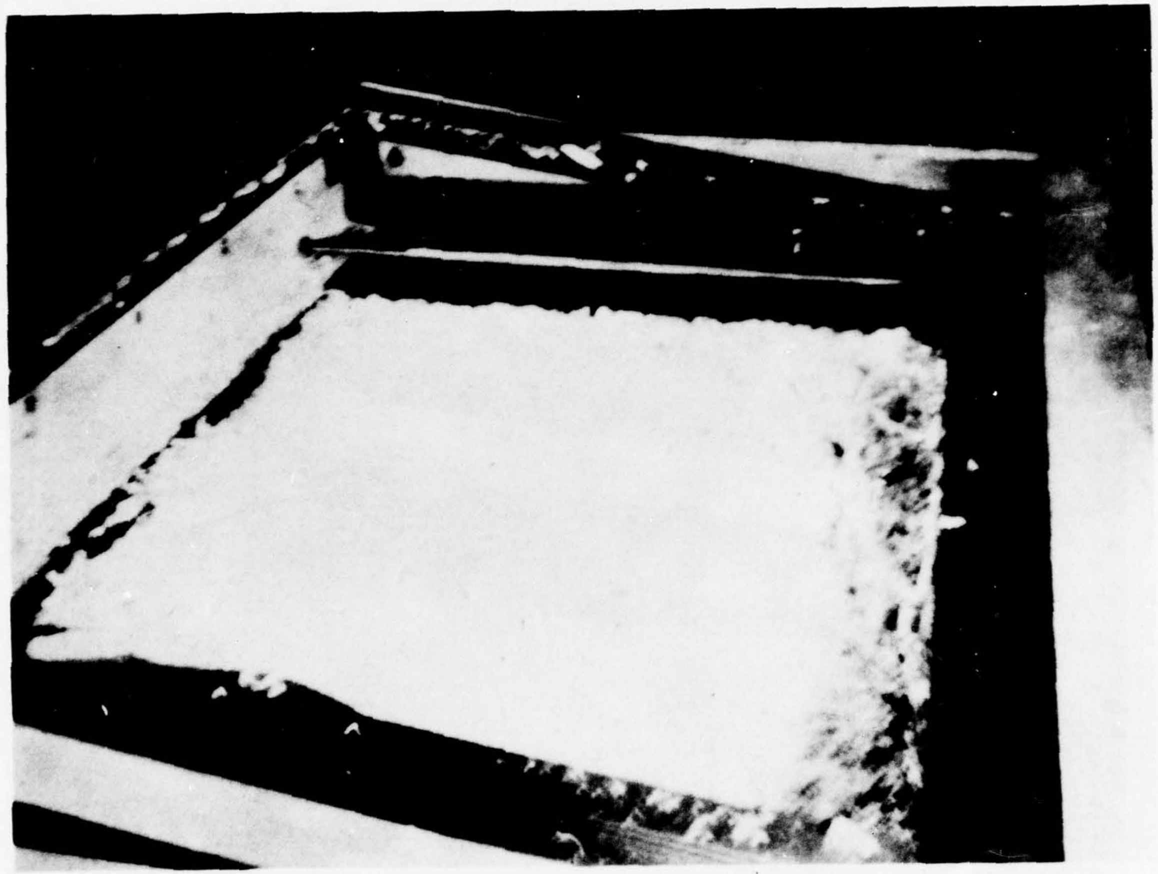

Fig 3 Typical Tempered Glass Breakage

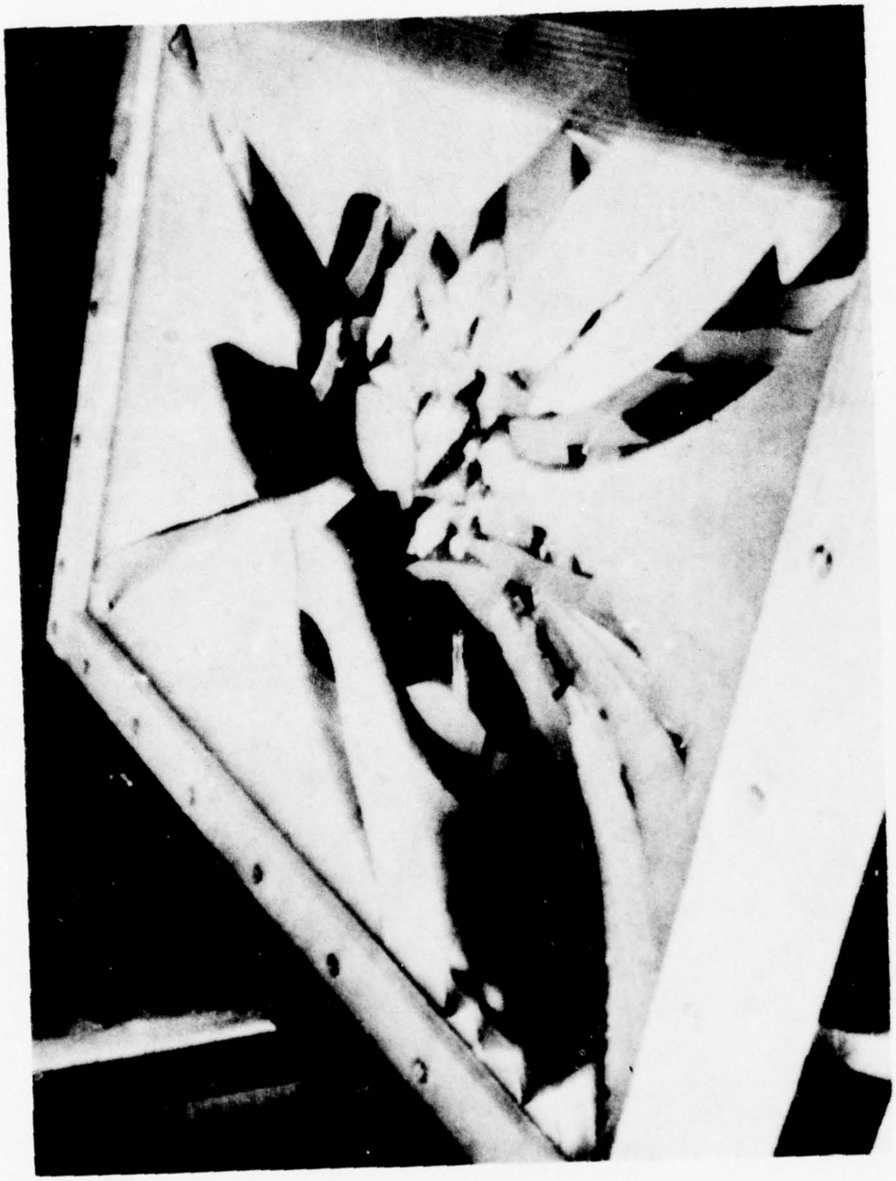

Fig 4 Typical Regular Glass Breakage

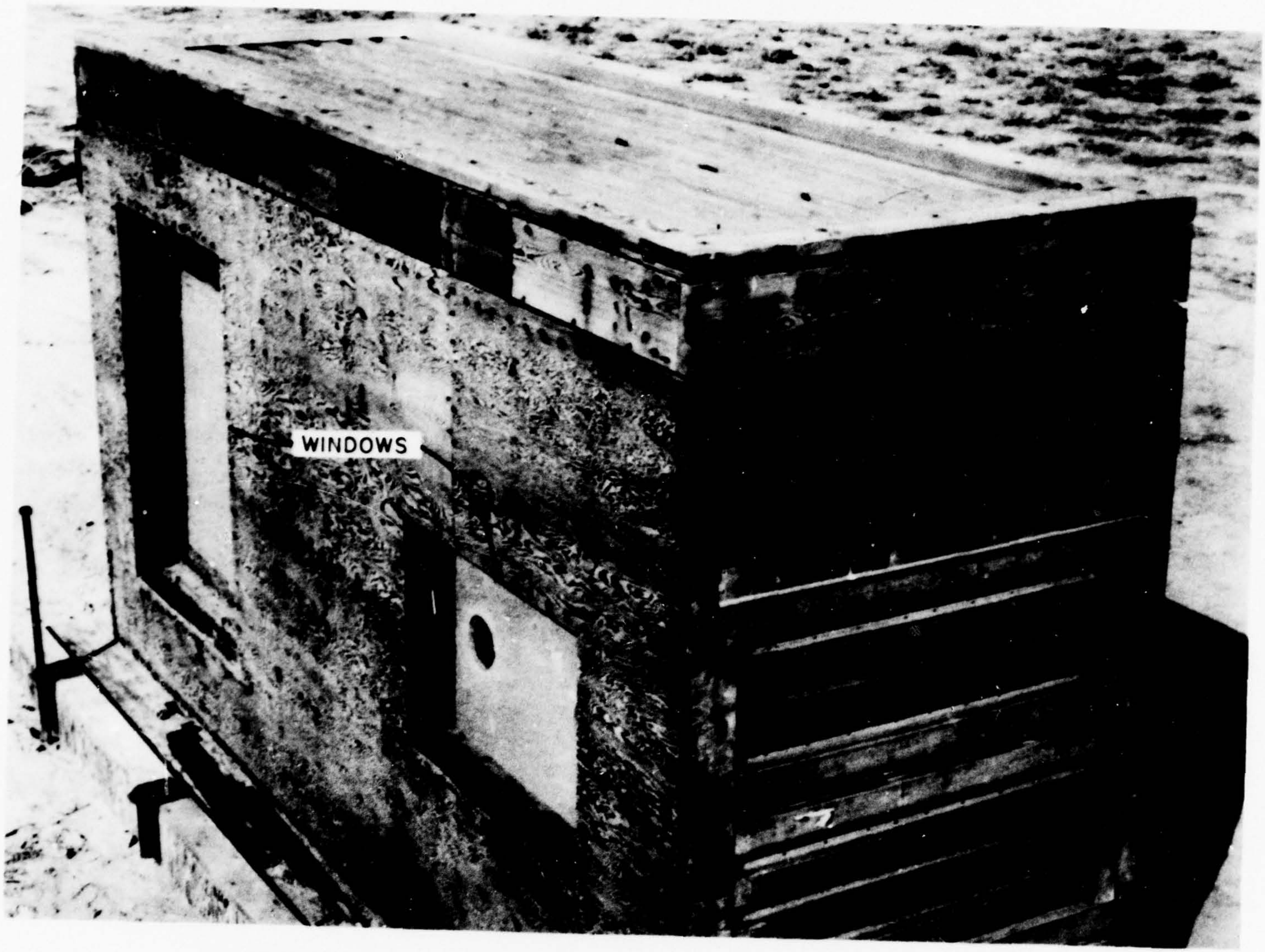

Fig 5 Test Structure B for Testing Steel Panels and Glass Windows

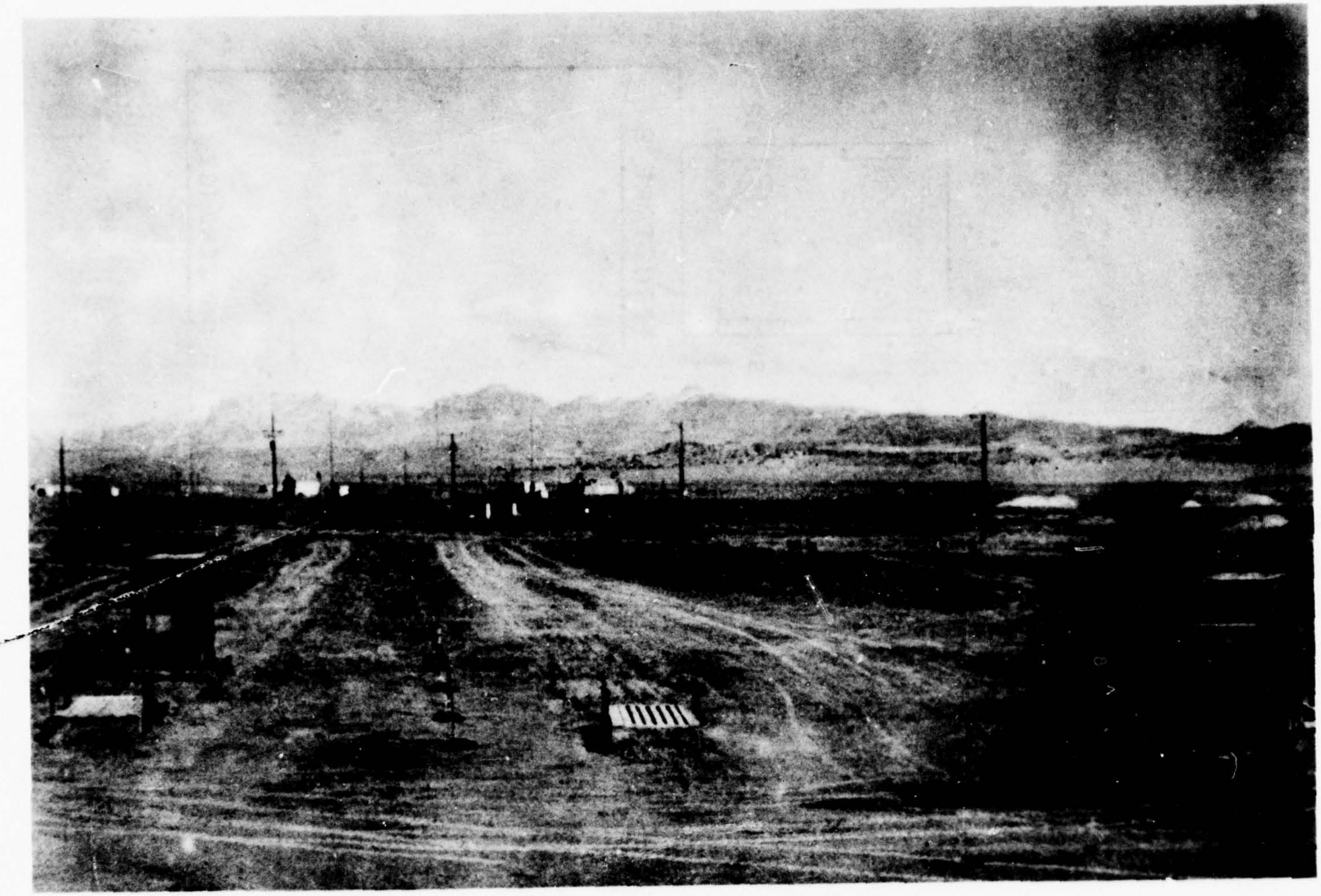

Fig 6   Layout of Test Structures and Pressure Gages

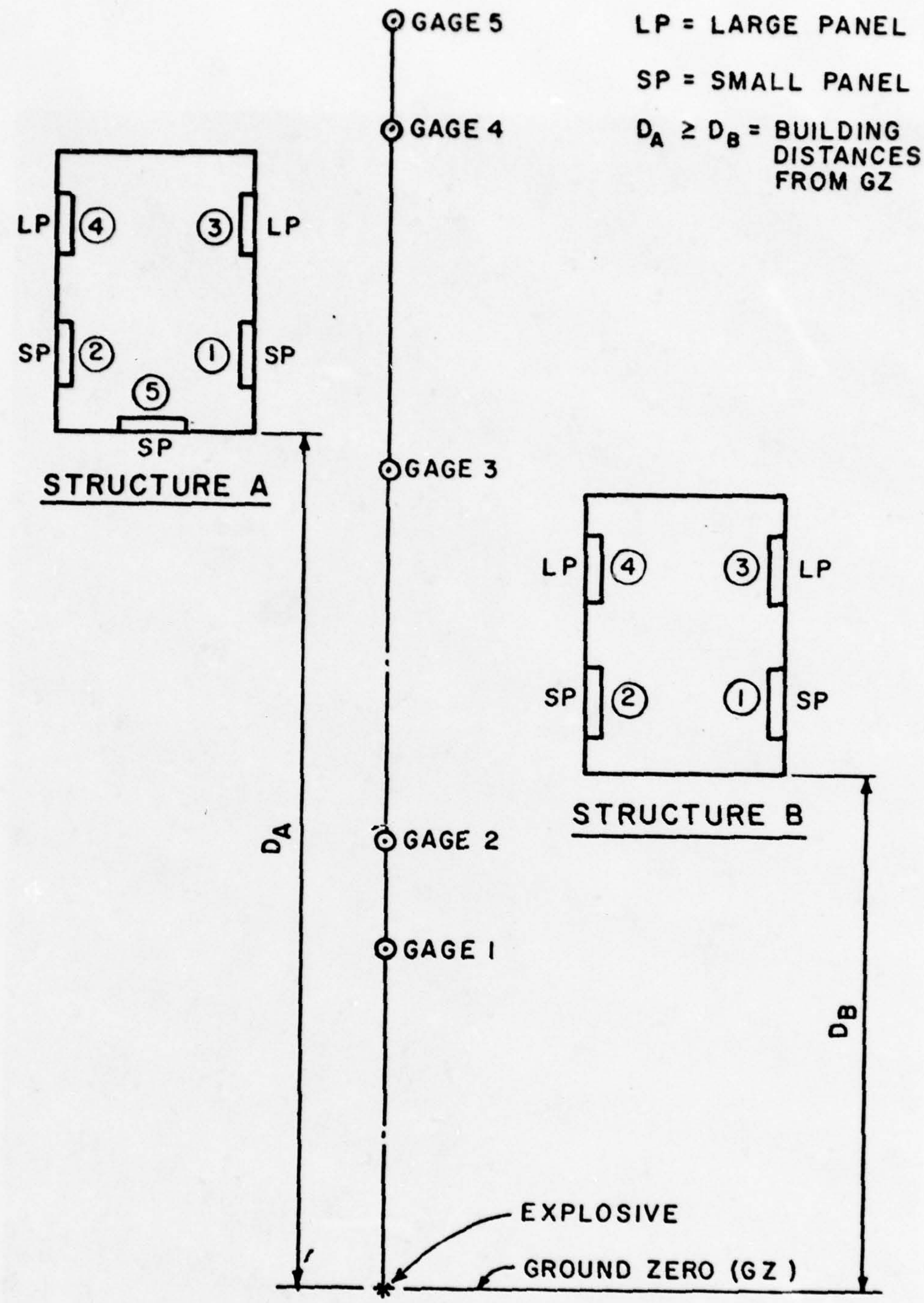

Fig. 7 Location of Test Structures and Pressure Gages

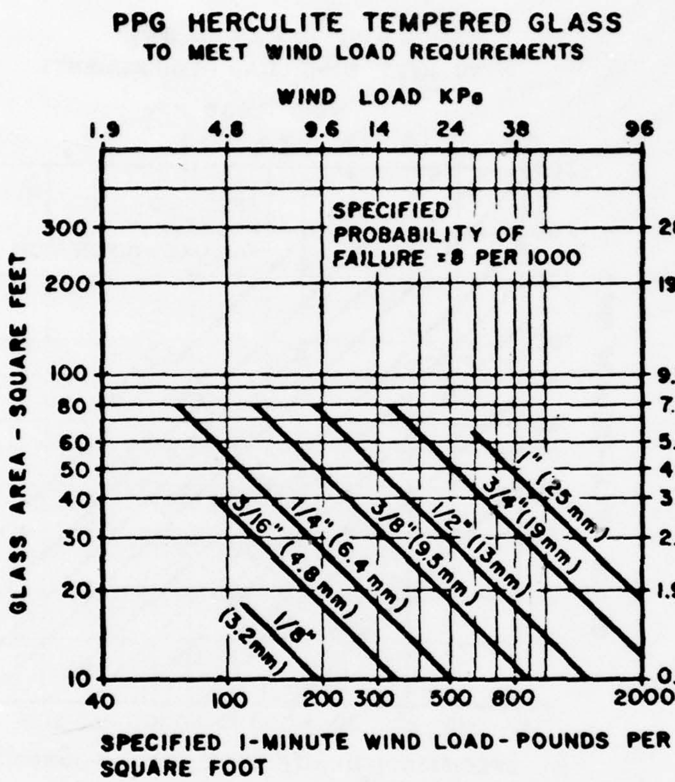

Fig. 8 Wind load capacity of Herculite tempered glass (Ref 7)

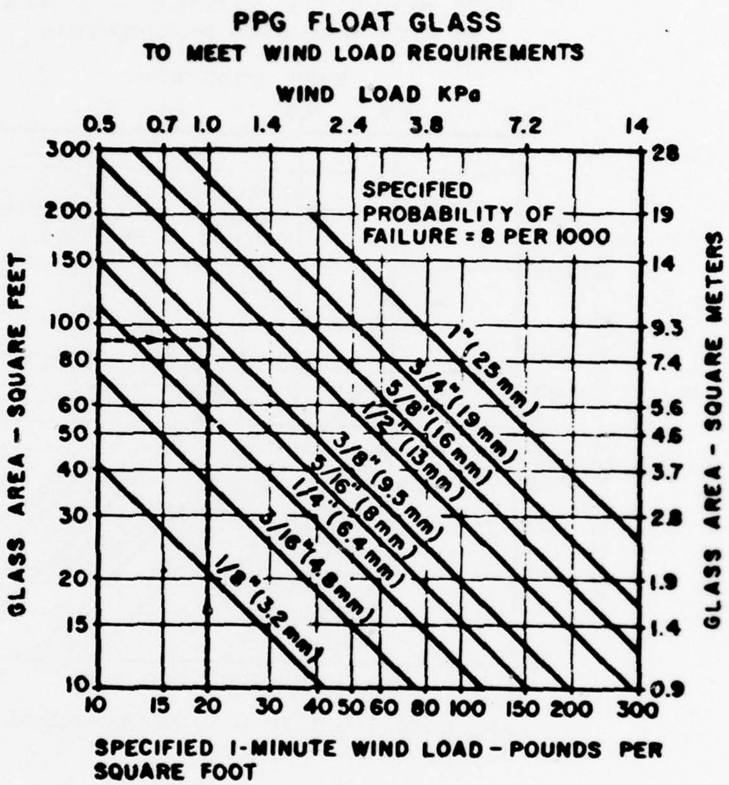

Fig. 9 Wind load capacity of regular glass (Ref 7)

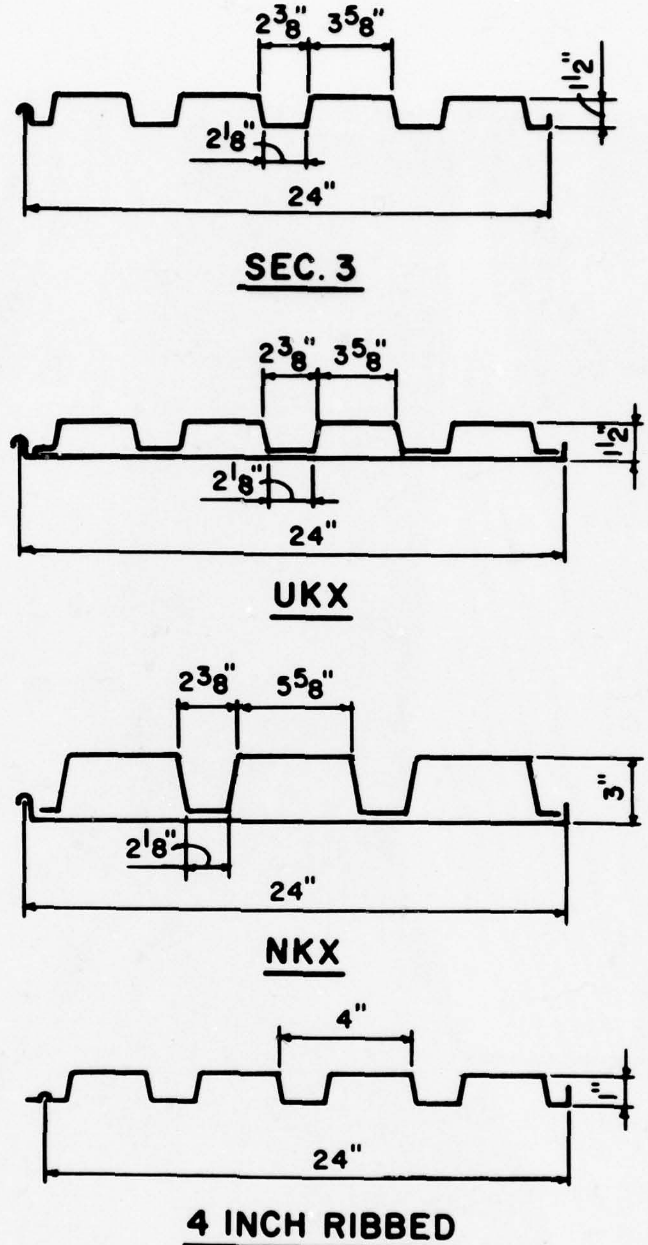

Fig 10 Cross-sections of Cold-Formed Steel Test Panels

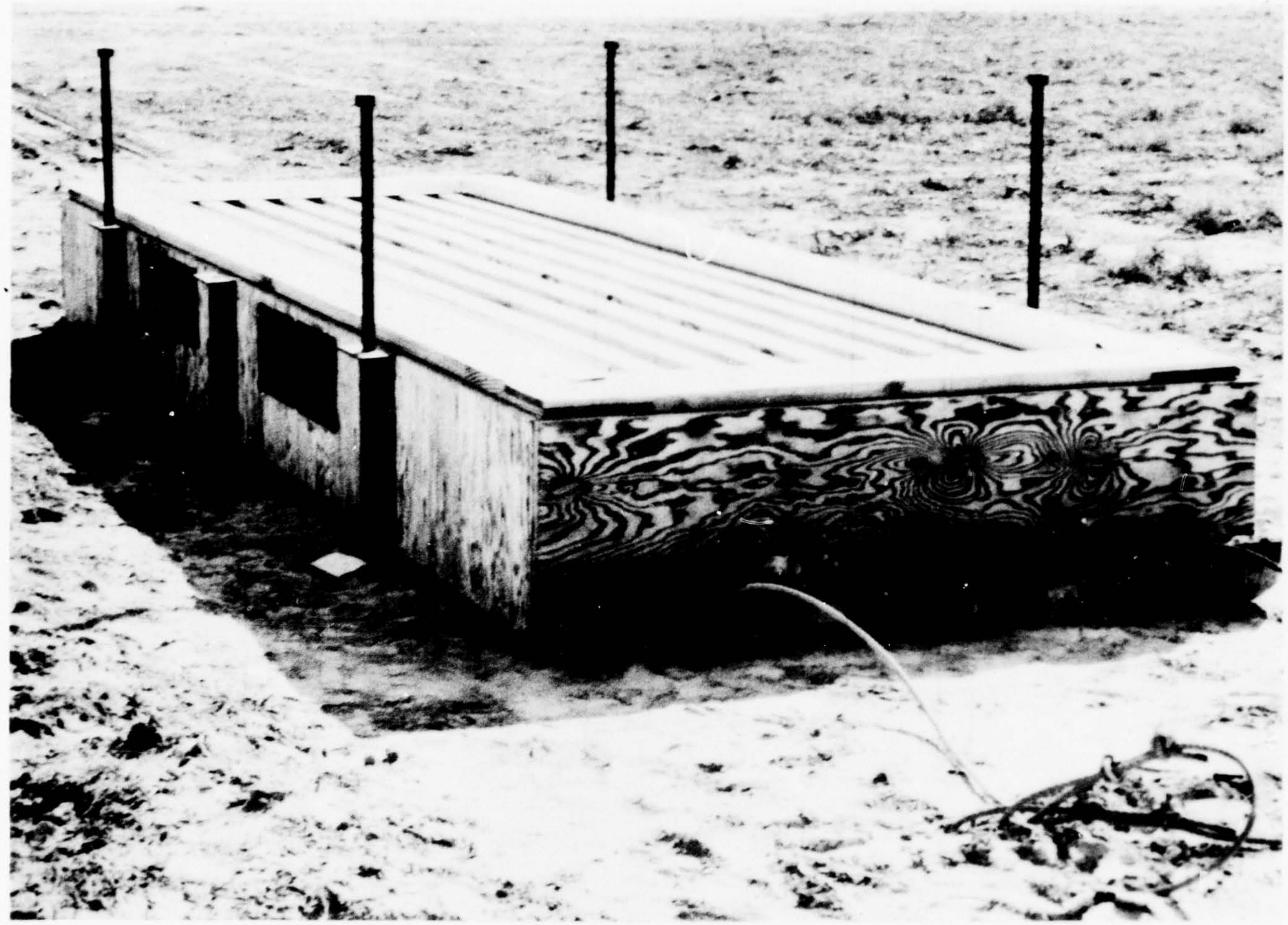

Fig 11 Test Structure C and D for Testing Steel Panels.

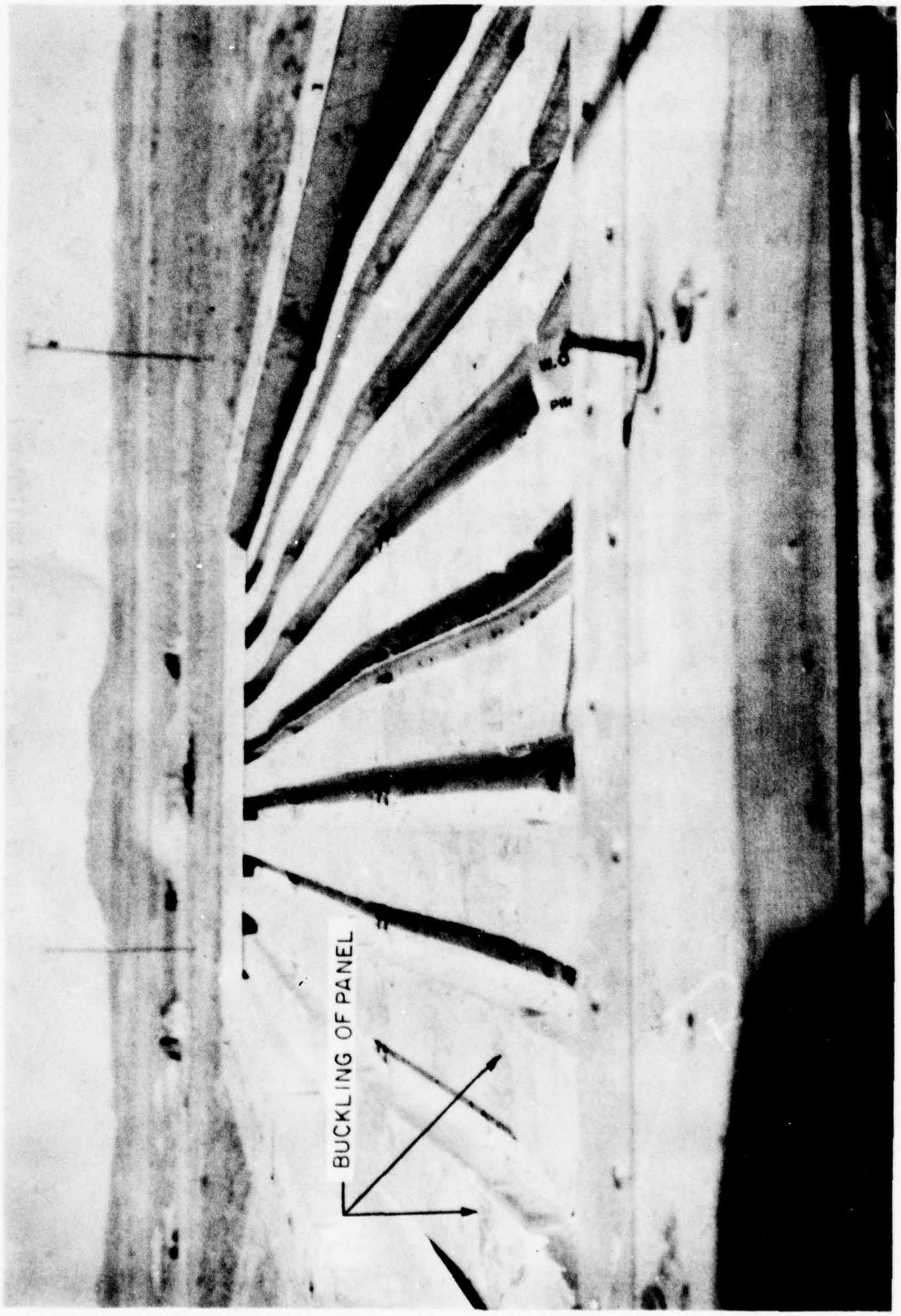

Fig 12. Damage to Sec. 3-20 Roof Panel

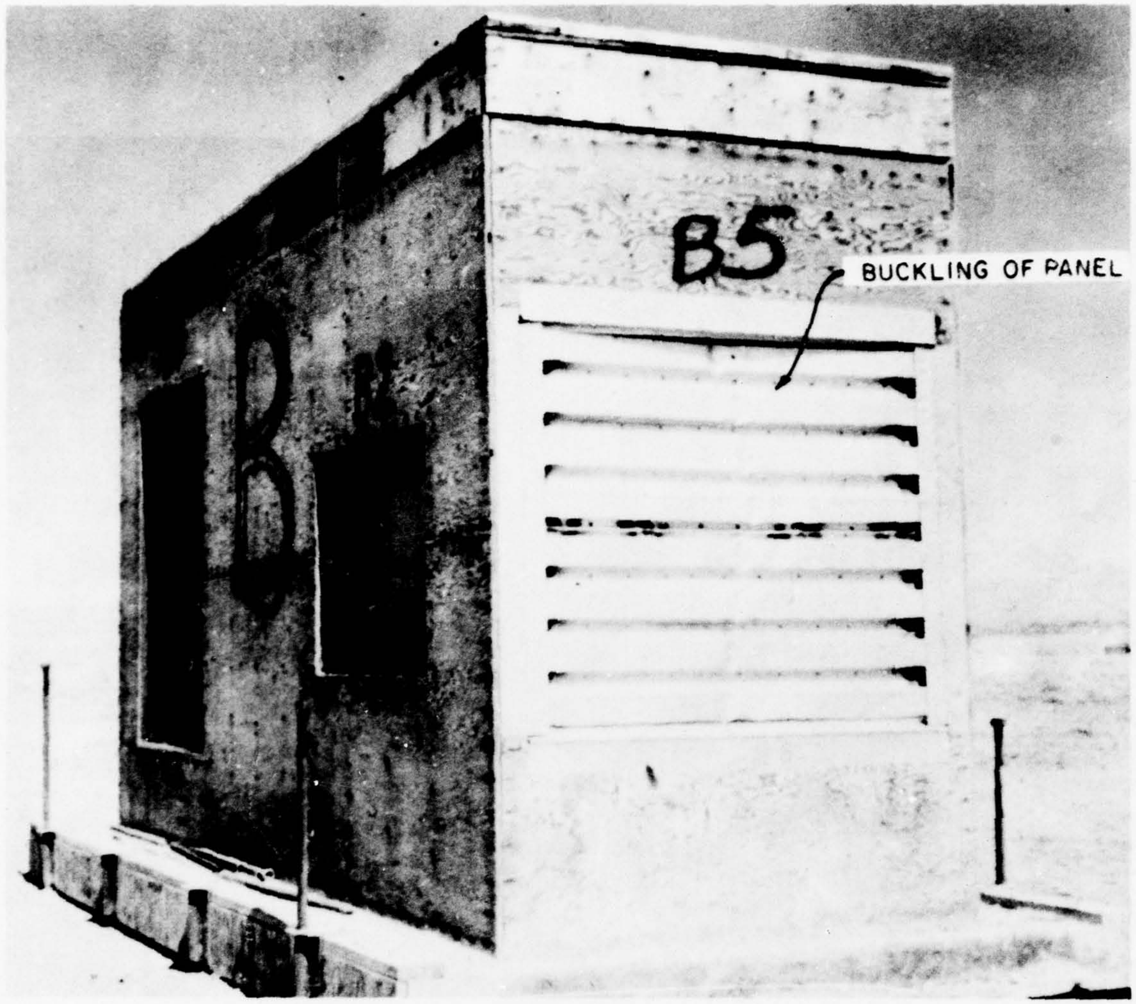

Fig 13 Damage to UKX 18-18 Wall Panel

Fig 14 Damage to NKX 20-20 of test 6

BLAST LOADED WINDOWS

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ABSTRACT

Windows or other glazed surfaces are becoming more and more common components of conventional buildings. The dominating features of glass as a material - transparency and aesthetic values - do not, however, include feasibility to act as protective structure when blast loading is at hand.

Experiments performed - and a theoretical consideration of the results - suggested a non-linear approach which resulted in a tentative design rule for dimensioning window panes which can be subjected to a blast load.

This paper presents all the results, experimental as well as theoretical. The work was initiated by the National Swedish Inspectorate of Explosives and Flammable Liquids and financially supported by the National Foundation for Workers' Protection and performed by the Royal Fortifications.

Symbols used are listed at the end of this paper.

INTRODUCTION

Modern buildings are often to a marked extent characterized by an obvious amount of windows and glazed surfaces. Neither glass as a material or windows as a construction element are, however, primarily appropriate as protective devices in case of an accidental explosion in the vicinity. Windows in a buildning can be said to correspond to the ear-drum in a human being, i.e. probably the weakest element in the system.

So knowledge of the behavior of glass and windows subjected to blast loads in urgently needed. Though studies and tests in this field are performed in several countries, no over-all survey of the total problem is known to the Author. This paper does not either claim to fill the gap. With the background of some recent tests in Sweden, however, an attempt will be made to

list what parameters are predominant in considering the case of a blast load.

For the material as such normal standard test procedures give a conception of the strength and an idea of the behavior under static loads. At suddenly applied loads the situation is different though. Due to the variation of force magnitude within finite time intervals we will get inertia forces which can be of considerable importance. Load-rise time and load duration here have a predominant influence. The vast number of parameters implies difficulties in an attempt to suggest a standardized test procedure for dynamic loads.

Some fundamental observations can, however, be noted. Thus material with a pronounced yield-limit will have this raised at transient loads. The same is often true for the ultimate strength of pure elastic materials, where furthermore also the Young's modulus will get a higher value.

Thus glass, considered as a pure elastic material, can for instance show the ultimate strength listed in Table 1 (according to Pittsburgh Glass Company).

TABLE 1

LOADING TYPE	DURATION	ULTIMATE STRESS
Sonic boom	0.1 sec	46.5 MPa
Gusty winds	5 - 10 secs	42.5 MPa
Wind loads	60 secs	31.0 MPa
Static load	2 hours	23.0 MPa

As can be seen from this table the ultimate strength for a certain type of glass can be doubled for a short duration load compared to the case where the loading is permanent. This doubling can of course not be taken for granted for all types of glass or loading situations.

We will, in the sequel, use the word glass as a comprehensive term for transparent material having no crystal structure or grain boundaries. The most common types are the commercially important crown glasses (sodium - calcium - silicate). The last decades also sheets of plastic materials have been available, especially in the building industry.

Through different manufacturing processes glasses with somewhat different characteristic properties can be produced. In principle, though, it can be said (especially for crown glasses) that the material behavior is ideally-elastic, i.e. glass is a brittle material.

Typical for glass is also that the tensile strength normally is considerably lower than the compressive strength, implying that fracture always occurs under some type of tensile strain and cracks will develop perpendicular to the direction of the principal tensile stress.

THEORY

Simple methods for calculation of material stresses in transversally loaded window panes are not at hand due to the fact that in the vicinity of point of failure we will get large deflections in comparison with the glass thickness. This makes elementary theory of plates irrelevant.

The problem is furthermore complicated by the fact that probability of failure at a given load is not only determined by type of glass and main dimensions but also strongly influenced by other factors such as frames, faults that may occur around the edges, thermal conditions etc.

As deflection at failure can be 5-10 times the thickness of the plate we will get membrane stresses which will strongly influence the fracture strength.

Determining for the stress calculations will then be, not only the plate dimensions, side-length a and b ($a \geq b$) and thickness h, but also deflection w under load.

An approximate solution can be reached under uniform load q by solving the third-degree equation

$$\frac{q}{E}\left(\frac{a}{h}\right)^4 = \frac{\pi^6}{192(1-\nu^2)}\left[(1+\gamma^2)^2\frac{w}{h} + \frac{3}{4}\left\{(3-\nu^2)(1+\gamma^4) + 4\nu\gamma^2\right\}\left(\frac{w}{h}\right)^3\right] \qquad (1)$$

where $\gamma = a/b \geq 1$

E = Young's modulus

ν = Poisson's ratio

The boundary conditions assumed are "pinned ends", i.e. freedom to rotate along the supports but blocked translation in any direction.

Diagram 1 shows the relation with $\nu = 0.25$ and $\gamma = 1$, 1.5 and 2.

With w/h known we can now calculate the maximum tensile stress σ in the center of the plate from

$$\frac{\sigma}{E}\left(\frac{a}{h}\right)^2 = \frac{\pi^2}{2(1-\nu^2)}\left[(\nu+\gamma^2)\frac{w}{h} + \frac{1}{4}\left\{(2-\nu^2)\gamma^2 + \nu\right\}\left(\frac{w}{h}\right)^2\right] \qquad (2)$$

This relation is shown in Diagram 2 for the same conditions as in the former diagram.

It can be noted from the given functional relations that they are markedly non-linear in spite of the assumption that the material studied is considered ideally-elastic. Of course this is due to the consideration of membrane stresses.

So far a static view is applied. We can combine the given eqs (1) and (2) to

$$\sigma = f\left(\frac{a}{b}, \frac{w}{h}, \nu\right) q \left(\frac{a}{h}\right)^2 \qquad (3)$$

The function f is given in Diagram 3 for $\nu = 0.25$.

For the blast loaded case we can use the same expressions as given above, exchanging the unifom load by a time-dependent load $q = p(t)$. Blast waves from explosions are often, neglecting the suction phase, written $p(t) = \hat{p} \cdot \exp(-\varkappa t)$ - see fig.

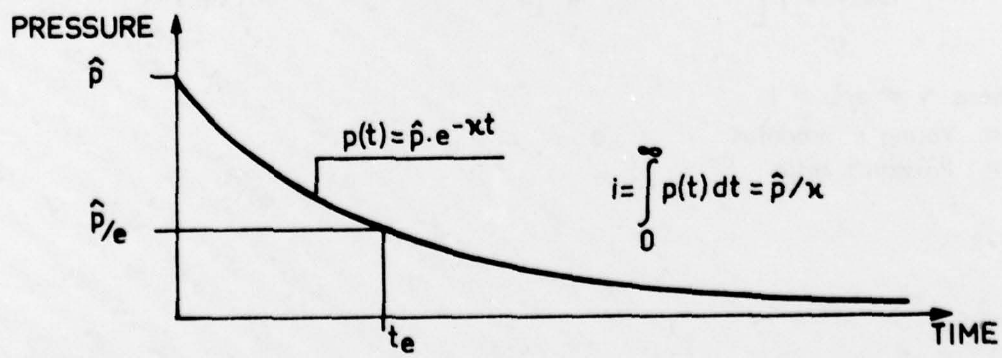
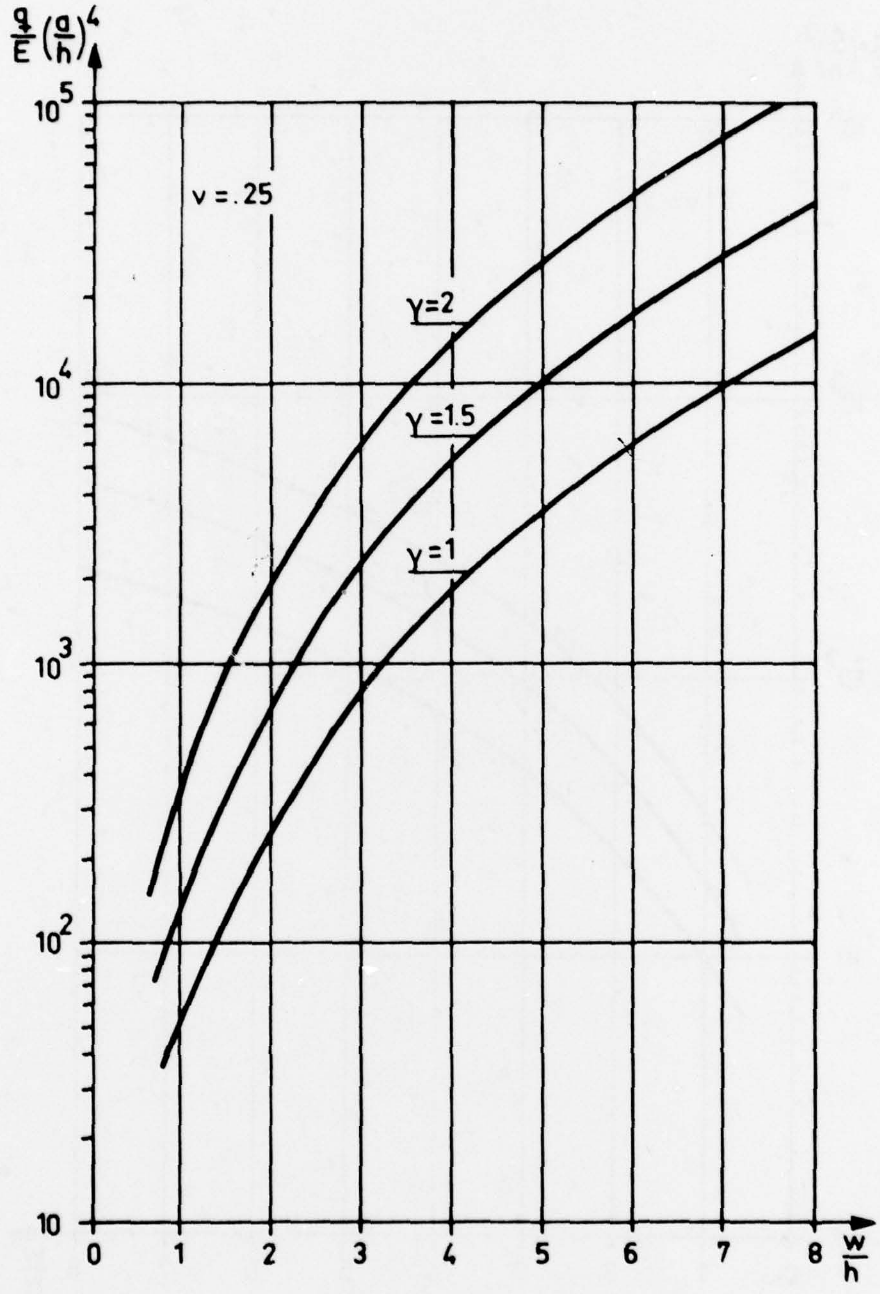
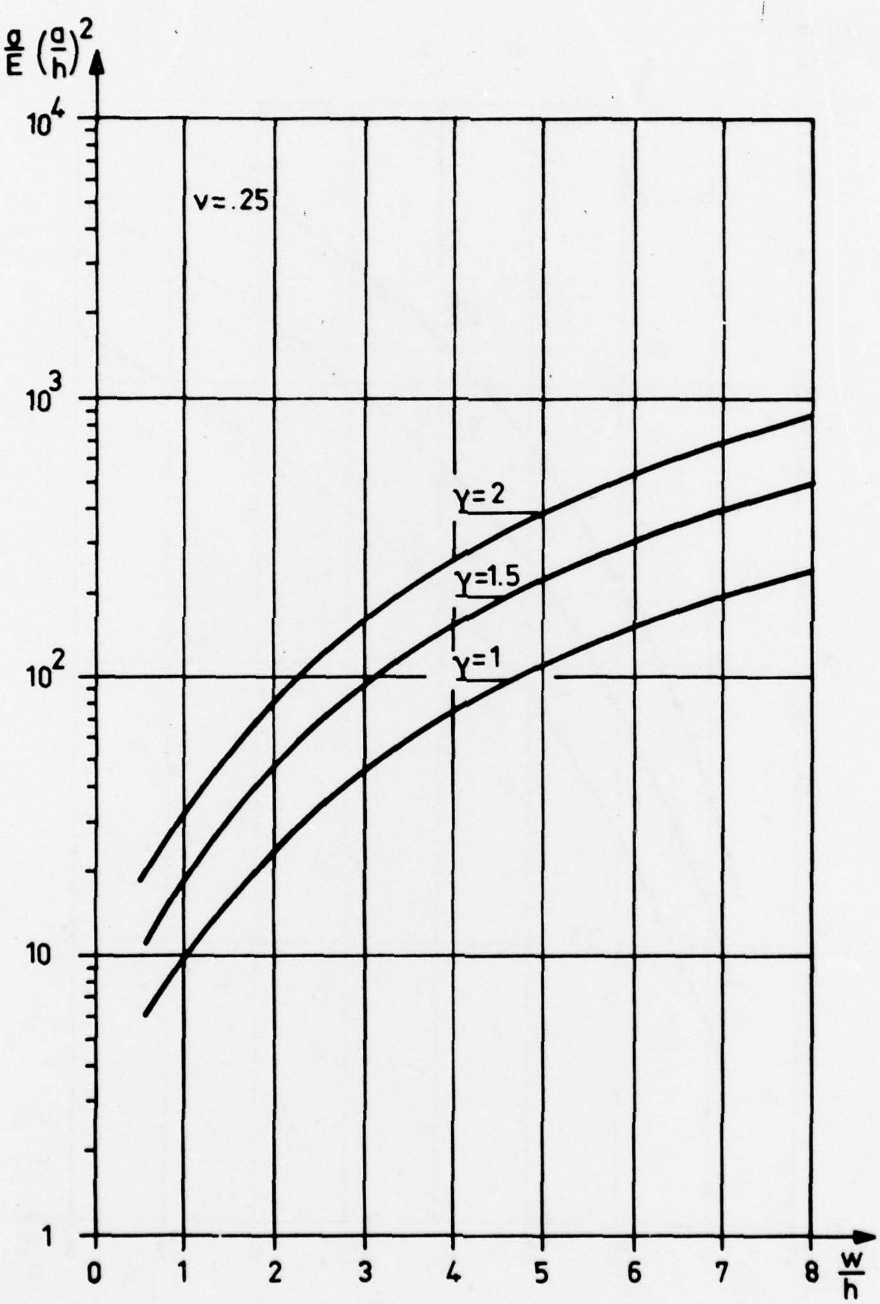


DIAGRAM 1



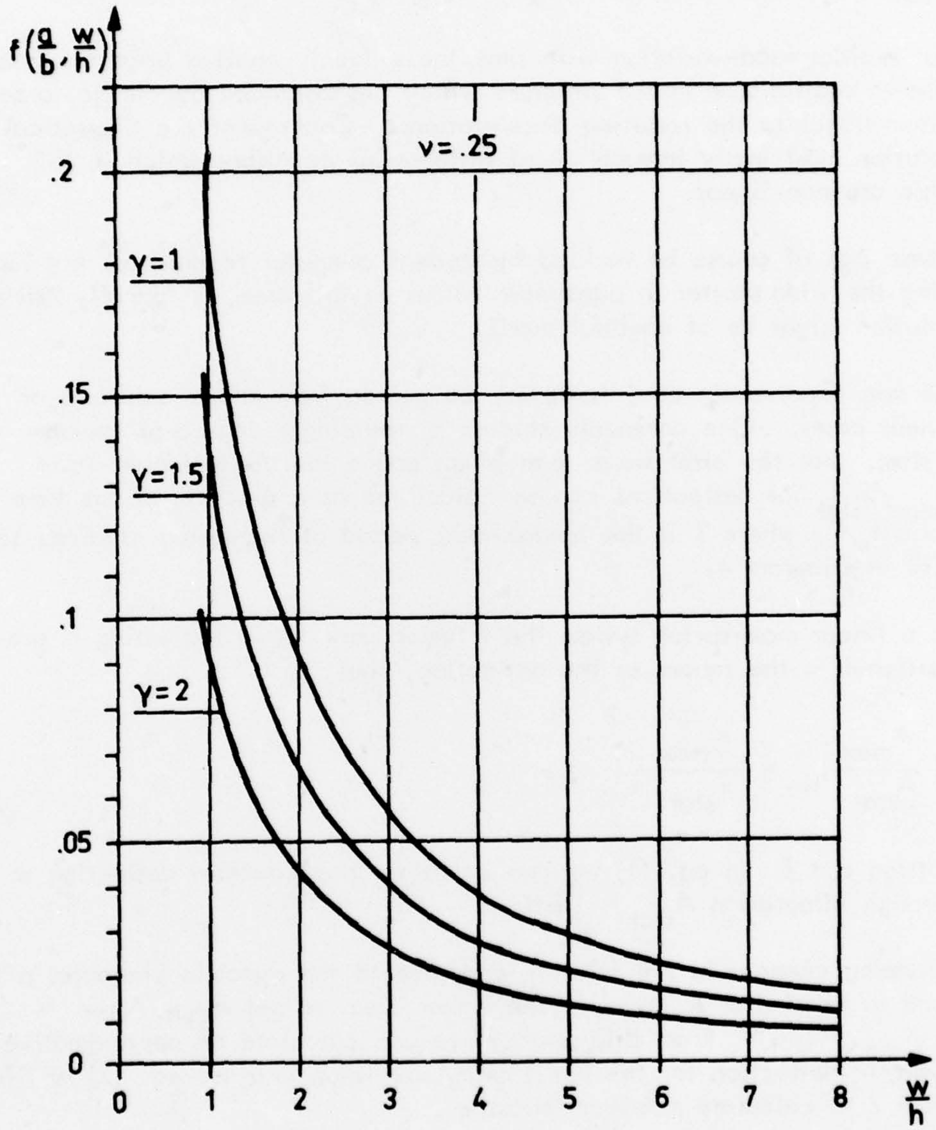
$\frac{q}{E}\left(\frac{a}{h}\right)^4$
10^5
10^4
10^3
10^2
10
$\nu = .25$
$\gamma=2$
$\gamma=1.5$
$\gamma=1$
0
1
2
3
4
5
6
7
8
$\frac{w}{h}$

DIAGRAM 2



$\frac{\sigma}{E}\left(\frac{a}{h}\right)^2$
10^4
10^3
10^2
10
1
$\nu = .25$
$\gamma = 2$
$\gamma = 1.5$
$\gamma = 1$
0
1
2
3
4
5
6
7
8
$\frac{w}{h}$

DIAGRAM 3



This expression has some convenient properties. Thus the impulse density i can be expressed as $i = \beta/\varkappa$, which means that through recording this and the front pressure $\hat{p}$ we can calculate the time-constant $\varkappa$ as the ratio $\hat{p}/i$. Furthermore it can be noted that the pressure is diminished to $\hat{p}/e$ after a time t_e which quite simply is equal to $\varkappa^{-1}$.

But besides load-variation with time, the suddenly applied pressure gives rise to oscillations in the structure which are balanced by inertia forces proportional to the resulting accelerations. Consequently a theoretical solution must imply integration of differential equations which in this case are non-linear.

These can of course be tackled by modern computer techniques, but regarding the wide scatter in parameter values in this case, a formally "strict" solution might be of doubtful merit.

Certain experiences can, however, be gained from known solutions of linear cases. One commonly studied is the single-degree of freedom system. For the blast wave form given above the dimensionless ratio x_{max}/x_{stat} for deflections can be calculated as a function of the time ratio t_e/T, where T is the fundamental period of the system studied, see plot in Diagram 4.

In a linear mass-spring system the interior work A in the spring is proportional to the square of the deflection, thus

$$\left(\frac{A_{max}}{A_{stat}}\right)_{lin} = \left(\frac{x_{max}}{x_{stat}}\right)^2$$

Putting $q = \hat{p}$ in eq. (1) we can calculate the maximum deflection w and through integration $A_{stat} = \int_w \hat{p}\,dw$.

Assuming changes in the interior work due to the dynamic character of the load to be similar to those in the linear case we get $A_{dyn}/A_{stat} = (x_{max}/x_{stat})^2$. From this relation we can calculate an approximative dynamic deflection for the non-linear case w_{dyn} and use eq. (2) or Diagram 2 to calculate maximum stress σ.

The procedure might seem somewhat complicated but might give reasonably acceptable results. The appropriateness for design purposes may be somewhat problematic and will be touched later on in a discussion.

At long durations ($t_e/T \geq 5$) we get for the linear case a ratio $x_{max}/x_{stat} \approx 2$. For the non-linear case we get the corresponding asymptote $w_{dyn}/w_{stat} \approx \sqrt{2}$.

For this case we can use Diagram 1 with $q = \hat{p}$, read w_{stat}, multiply by $\sqrt{2}$ to get a w_{dyn} for use in Diagram 2.

EXPERIMENTS

Some recent tests performed in Sweden by the Royal Fortifications contain measurements of all parameters of main value for an attempt to make an analysis. The results from tests and calculations are given in Table 2. The window-panes were tested in a shock-tube with reflected blast-pressures from detonating TNT-charges. The pressure-time histories were recorded using piezo-electric transducers the signals of which were taken by a tape-recorder. The experimental stresses given are evaluated from strain-gauges glued to the center-point of the rear pane side. Values for Young's modulus are given by the manufacturers and the fundamental periods were established on the mounted test objects.

The given and analyzed pressure levels are those which the panes could sustain and where readable strain-records were obtained.

As can be seen the agreement between calculated and measured values is quite close. Thus the sketched approximate procedure for calculating stresses under this type of load can be said to be justified to a certain extent.

TYPES OF GLASS

Following comments can be made as what regards the different types of glass tested. Window glass denotes the standard type of machinemade glass commonly used in the building industry. Tempered glass denotes qualities which have undergone thermal hardening. Acrylic plastic is sheeting from polymethylmetacrylate (PMM) or plexiglass. Lexan is the GE trade mark for a plastic sheeting of polycarbonate type. The VHR (Verre à Haute Resistance - High Resistance Glass) finally is a special chemically tempered glass in double sheets with an interlayer from polyvinylbutyrale. At the tests we used a type, mark 33 E, consisting of two 3 mm panes with a 1.9 mm plastic interlayer.

TABLE 2

	GLASS						TESTS			CALCULATED		
No.	TYPE	a mm	b mm	h mm	E MN/m^2	T ms	$\hat{p}$ bar	i barms	$\bar{\sigma}$ MN/m^2	$\left(\frac{w}{h}\right)_{dyn}$	σ MN/m^2	$\sigma/\bar{\sigma}$
0	WINDOW	1360	960	4	$5 \cdot 10^4$	60	.036	.07	6.5	.83	5.9	.91
1	DO. PLASTIC ON REAR SIDE	1360	960	4	$5 \cdot 10^4$	50	.1	.5	26.5	2.40	25.9	.98
2	DO. PLASTIC ON BOTH SIDES	1360	960	4	$5 \cdot 10^4$	50	.1	.5	26.0	2.40	25.9	1.0
3	WINDOW	1360	960	3	$5 \cdot 10^4$	80	.036	.05	4.5	.93	3.8	.84
4	ACRYLIC	1360	960	8	$3.2 \cdot 10^3$	70	.17	1.5	12.0	3.16	10.2	.85
5	VHR	1310	905	7.9	$7 \cdot 10^4$	30	.17	1.5	48.5	1.25	61.5	1.27
6	LEXAN	1350	950	8	$2.3 \cdot 10^3$	50	.7	15.0	31.9	7.95	35.6	1.12
7	TEMPERED	1350	950	8	$7.5 \cdot 10^4$	35	.28	3.5	93.0	1.65	91.2	.98
7/2	TEMPERED	950	620	8	$7.5 \cdot 10^4$	17.5	.7	15.0	163.5	1.54	191.6	1.17
7a/2	WINDOW	950	620	8	$5 \cdot 10^4$	21.5	.17	1.5	45.0	.80	53.3	1.18

It should be noted that the loads given in Table 2 are those which left intact panes without any permanent deflections.

From strain-records it can be stated that the frequency of the panes varies with the load, being higher in the initial phase of the deflection-time history. Thus the frequency is dependent on the amplitude of the movement which is symptomatic for non-linear dynamic systems. Thus it is evident that *membrane stresses* have been at hand justifying the considerations made. The period T used in the calculation is valid at small deflections.

Generally can be said that glazed surfaces are not very suitable for resisting blast loads. If they are nevertheless necessary the daylight measures should be as small as possible and the panes used as thick as possible.

Regarding blast loads polycarbonate glasses seem preferrable to other types, followed by the tempered glasses. A plastic coating on one or both sides of a pane does not in principle enhance the strength but can somewhat influence the shatter pressure and can, at a slight overload, keep the splinters together so that the fragments do not fly around in swarms.

Wire glasses are not to be recommended as the metallic nets evidently give raise to fracture initiations which can lower the breaking pressure considerably. Torn and exposed net can furthermore be hazardous projectiles.

Looking at secondary effects, i.e. what happens after an overload, implies consideration of form, size and velocity of fragments.

At slight overloads a plastic coating can have a favourable influence. This is especially the case when the plastic sheeting is used as an interlayer as in the laminated VHR glasses. In this case there is hardly any free fragments at all as long as the frame manages to keep the deformed pane.

Tempered glass gives at breakage a vast number of dangerous fragments with high velocity and substantial scattering.

Acrylic plastic has a tendency to break in a number of fairly large pieces with unpleasant sharp edges, which can be the case even with other plastic sheeting as for instance the polycarbonate glasses. Velocities are dependent on the degree of overloading. Large pieces can be found dancing at moderate wind velocities.

The simplest way to somewhat make the situation better at existing structures is to apply plastic sheet-coating.

FRAMES

No doubt the shock-withstanding ability of a window is a problem of frame design. It might be possible to specify at least some glass types to withstand any shock pressure the frame or the ordinary building structure can. Obviously, it would be pointless to specify a glazing material or window frame the strength of which is far in excess of the building structure strength. A sufficiently rugged window frame will, however, probably become a difficult and expensive production problem. Of course, if shock resistant window frames are desired, it would always be advisable to carry out dynamic shock wave tests to determine the optimum design.

So far the theoretical treatment has been confined to the glass plate regarded as an elastic system. For several reasons, though, a window as a system is very strongly influenced by the clamping conditions, i.e. the supporting frame.

The degree of clamping thus influences the fundamental frequency. An expression for this can be written

$$f = \frac{2\pi}{a^2}\sqrt{\frac{D}{\rho h}}\,\varphi \qquad (4)$$

where $D = Eh^3/12\,(1-\nu^2)$ is the plate stiffness and ρ is the density. The coefficient φ is a function of the clamping degree and can be written

Free supports $$\varphi = \frac{1}{4}(1+\gamma^2) \qquad (5)$$

Clamped supports $$\varphi = \frac{1}{3}\sqrt{\frac{7}{2}(1+\gamma^4)+2\gamma^2} \qquad (6)$$

The higher frequency the shorter period which, as mentioned, is of certain importance when the load has a limited duration. For a square plate the clamped frequency is twice as high as in the free support case and this ratio escalates with raising side-length ratio $\gamma = a/b, (a \geq b)$.

Frames should allow some rotation around the supports but be sturdy enough to prevent large deformations in the frame itself. Some consideration should be paid to the possibility for the glass sheet to endure elongations due to changes in temperature.

Conditions around the frame can have other effects, though. A very stiff clamping brings about a risk for cracking the glass when mounting, especially so as the glass-edge through cutting can be a presumptive initial source of fracture. A stiff mounting can furthermore have as a consequence that the window pane snaps over the frame edge preventing energy consumption through large deflection.

Ideally the pane should have an elastic support preventing translations under load but making a limited rotation around the edges possible. This claims of course that the frame should stand the support forces and be able to sustain the membrane stresses in the deflected window pane.

As a rough estimate the frame could be designed for a force /lengthunit V perpendicular to the pane and a force/ unit of length H in the plane of the plate

$$\left.\begin{aligned} V &= \frac{1}{4} \cdot q a \\ H &= \frac{1}{8} q \cdot \frac{a^2 - 4w^2}{w} \end{aligned}\right\} \qquad (7)$$

DESIGN

As mentioned a large number of parameters influence the dimensions of a window pane to make it endure a certain blast pressure. A survey of the factors believed to be most important has been made, which led to functional relations which is in good agreement with experimental results.

The relations are, however, due to the assumed non-linearity of the system, rather complex and not very adapted to calculations to get rough estimates. A simplified method of calculation or a rule of thumb is desirable.

In the literature one can find expressions of the form

$$q = C \frac{h^2}{A} \qquad (8)$$

where A is the daylight area and C an empirical constant. The latter is often said to be a function of the side-length ratio γ, which is no doubt true for the elementary plate theory.

The relations deduced in this paper can also be transformed to a form simular to eq. (8). An extended analysis shows however, that the factor C is a rather complicated function of γ, w/h, ν, σ and E; in addition to this there is a dependency on the nature of the load expressed by the characteristic time t_e.

With certain reasonable approximations we can transform earlier derived relations to an expression for the shatter pressure in bars

$$q = k \ (y + \lambda y^3) \ (\frac{h}{T})^2 \tag{9}$$

Where

h = thickness in mm
T = fundamental period in msecs
y = w/h
λ = $1 + 0.3\gamma$ where $\gamma = a/b \geq 1$
and
$k = \frac{1}{4} \pi^4 \rho \cdot 10^{-5}$ and ρ = density in kg/m^3

Putting ρ for crown glass to 2500 kg/m^3 and for polymeric products to 1200 kg/m^3 we get for

Crown glass	$k \approx 0.6$
Plastic sheeting	$k \approx 0.3$

Now let us tentatively assume the following maximum deflections allowable

For	Window glass	$w/b \leq 0.01$
	Tempered glass	$w/b \leq 0.02$
	Plastic sheeting	$w/b \leq 0.035$

The fundamental period $T = 1/f$ can be calculated from given formulas or measured on actual structures.

For time-dependent loads with a steep front, i.e. typical blast waves, the ratio $q/\hat{p}$ can be read from the semi-empirical Diagram 5 as a function of t_e/T. The characteristic time t_e can easily be found as $i/\hat{p}$. It can be shown that the Diagram 5 should have an asymptote for $q/\hat{p} = 8/3$ which consequently is valid for long duration blast waves. The experimental material available so far is not sufficient to form the base for a statement

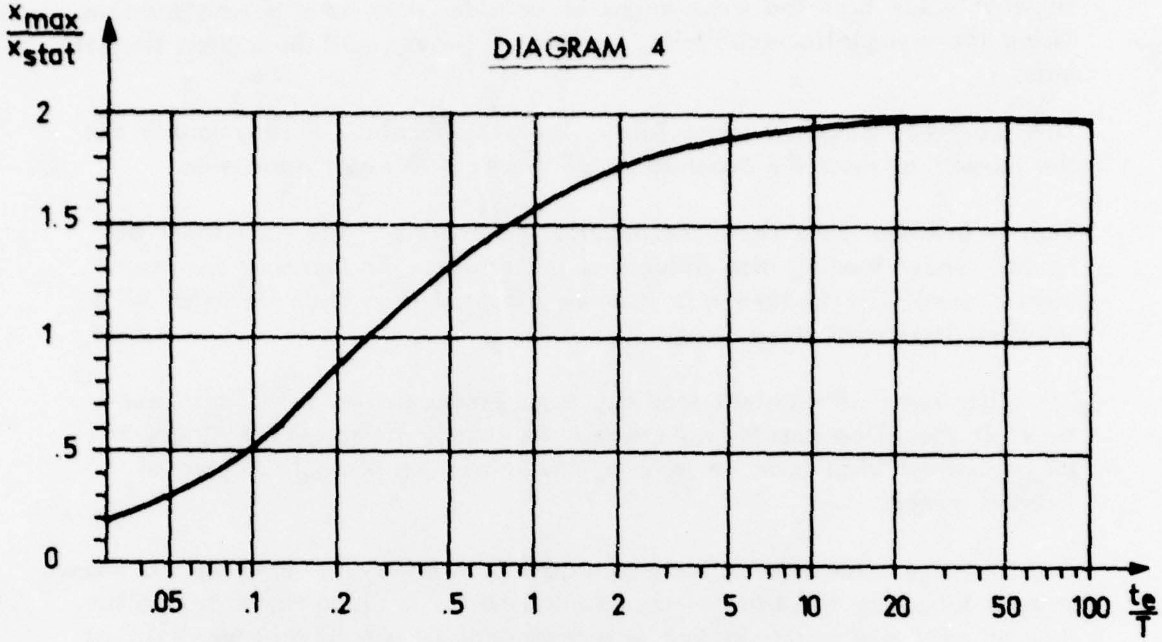


DIAGRAM 4
xmax / xstat
2
1.5
1
.5
0
.05
.1
.2
.5
1
2
5
10
20
50
100
te / T

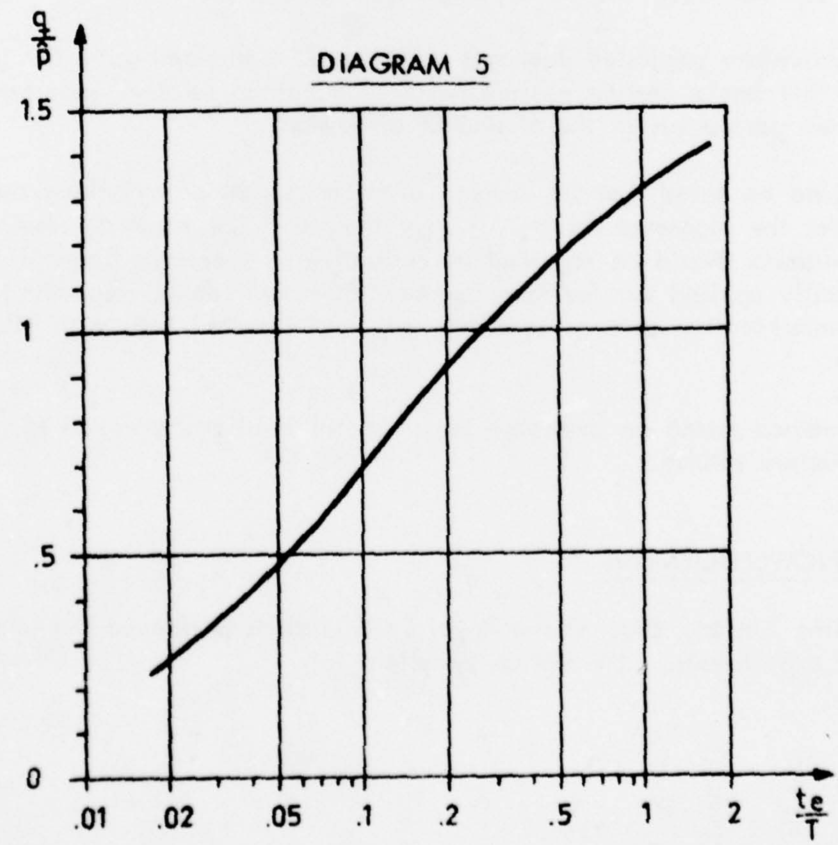


DIAGRAM 5
q / xp
1.5
1
.5
0
.01
.02
.05
.1
.2
.5
1
2
te / T

at what value t_e/T the wave might be considered to have a long duration. Using the asymptotic value will, however, always result in a $\hat{p}$ on the safe side.

This procedure proposed seems fairly simple to handle. Furthermore it has the benefit to show the dependency of the most relevant parameters.

Thus it involves dimensions and material parameters. The non-linear behavior under loading also influences the results. Furthermore we here have a possibility to take into account the load-time characteristics at a transient load with steep front.

For other types of transient loading, e.g. pressurewaves with finite rise-time, it should be possible to convert the actual pressure-time history to an equivalent blast load by studying the effects on a single degree of freedom system.

The tentative allowable deflections stated give a way to limit the maximum stresses following the train of thought that stress is proportional to the radius of curvature which in turn is proportional to angular change (e.g. at the supports) which can be expressed through w/b.

The procedure suggested does not claim to be a decided truth but gives never the less a certain possibility to estimate the relative importance of relevant parameters in the choice of dimensions.

It should be noted that the amount of experimental data forming the foundation for the suggested relation is very limited. Consequently results from calculations should be regarded as indicative. A certain factor of safety is implicitly applied but far from an order of magnitude corresponding to accounted scatter in e.g. tensile strength of standard tests with glass material.

The method tested on available experimental results has proven to give satisfactory results.

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LIST OF SYMBOLS

A	daylight area (square meter, m^2)
A_{max}	interior work at maximum deflection (newtonmeter, Nm)
A_{stat}	interior work at static load (Nm)
A_{dyn}	interior work at dynamic load (Nm)
a	sidelength of pane ("long side") (m)
b	sidelength of pane ("short side") (m)
C	empirical constant (N/m^2)
D	plate stiffness (Nm)
E	Young's modulus (N/m^2)
f	frequency (Hz, 1/s)
H	force/unit length in plane of plate (N/m)
h	plate thickness (m)
i	impulse density (Ns/m^2, bar · s)
k	constant $= \frac{1}{4} \pi^4 \cdot \rho \cdot 10^{-5}$
$\varkappa$	time constant (1/s)
p	pressure (N/m^2, Pa or bar)
$\hat{p}$	peak pressure (N/m^2)
q	uniform load (N/m^2)
T	fundamental period (s)
t	time (s)
t_e	time constant (s)
V	force/unit length perpendicular to plate (N/m)
w	deflection (m)
w_{dyn}	deflection at transient load (m)
w_{stat}	deflection at static load (m)
x_{max}	maximum deflection at dynamic load (m)
x_{stat}	maximum deflection at static load (m)
ν	Poisson's ratio (-)
γ	sidelength ratio, $a/b \geq 1$
σ	stress (N/m^2)
ρ	density (kg/m^3)
φ	coefficient (-)